Properties and Distortion of Douglas-fir with Comparison to Radiata Pine

A thesis submitted in partial fulfilment of the requirement for the degree of Masters of Engineering in Chemical and Process Engineering

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Table of content

List of figures

List of tables

Abstract

The objectives of this study were to investigate stability related basic wood properties and to determine stability performance of New Zealand grown Douglas-fir and those of radiata pine wood. In this study, nine 60-year old Douglas-fir trees and thirteen 26-year old radiata pine trees were selected from forests in Canterbury region. From these trees, 36 discs of 200 mm thick (13 for Douglas-fir and 23 for radiata pine) and 388 boards with dimensions of 100mm × 50mm × 4.8m (210 fro Douglas-fir and 178 fr radiata pine) were prepared.

From the prepared discs, 515 specimens (204 for Douglas-fi and 211 for radiata pine) were prepared for green moisture content (MC) and basic density measurements, The same total number of 515 specimens (205 for Douglas-fir and 210 for radiata pine) were also prepared for shrinkage measurements. From the green MC specimens, green weight, volume and oven-dry weight were measured while for the shrinkage specimens, dimensions and weights were measured at equilibrium for nine humidity conditions. These data were used to analyse basic wood properties and moisture uptake characteristics for both Douglas-fir and radiata pine. Variation of shrinkage within a tree and between trees was also studied for both species. After this, selected specimens (36 for Doulas-fir and 36 for radiata pine) were further tested in water immersion for water repellence examination.

The 388 full size boards (100mm×50mm×4.8m) were used for studies on distortion and acoustic properties at a sawmill (Southland Timber Ltd.). Dimensions, weights and acoustic velocity were measured from each board before and after drying. These data were used to analyse distortion and strength characteristics for both Douglas-fir and radiata pine. Comparison of the relative stability of full sized Douglas-fir and radiata pine structural timber was investigated in this study.

The results from small sample study confirmed that Douglas-fir is much stronger, has lower longitudinal shrinkage and lower gradient in corewood which can be used to explain the better dimensional stability of Douglas-fir than radiate pine although there is significant variability in the shrinkage for both Douglas-fir and radiate pine. In

water immersion tests, Douglas-fir has better water repellency property than radiata pine over 2000 hours period during water immersion.

Under the same commercial practice in sawing and kiln drying, it is clearly shown that Douglas-fir timbers were straighter with lower levels of distortion than radiata pine at similar final moisture content. It is also interesting to note that the final moisture content in a range of 13-18% for Douglas-fir did not have significant impact on timber distortion but a negative trend was observed for radiata pine with MC in a range of 9 -14%. Tree heights showed clear influence on twist for radiata pine timbers, but it was not clearly observed from Douglas-fir timbers. Corewood proportion is found to have negative impact on the timber distortion for both Douglas-fir and radiata pine. Douglas-fir timbers showed much higher average acoustic MOE value than radiata pine timbers at similar final moisture content.

Because of the various proportion of corewood, the shrinkage varied greatly along the stem height and along the disc radius direction for the two species. This variation caused the difference of distortion between corewood, outerwood and transition wood, but the difference between butt log, middle log and top log is inconsistent. Therefore, it is recommended that the corewood proportion to be a criterion for the timber pre-sorting.

Variation of stability performance between trees was also found to be significant for the two species, and methods need to be developed for log sorting as well to reduce the timber distortion degradation. Non-destructive testing method such as acoustic tool may be offered to be a new approach for sorting logs, but it is also necessary to be aware of the significant difference between species.

The outcome from this project includes better understanding of Douglas-fir for structural applications. The conclusion can be drawn that Douglas-fir has superior quality for its strength, durability and moisture resistance. Douglas-fir is also claimed to have uniform properties and thus to be more stable compared to radiata pine. Douglas-fir timbers showed much higher acoustic MOE value than radiate pine timbers as similar final moisture content.

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Chapter 1 Introduction

1.1 Background

Douglas-fir is a major commercial forest species of the Pacific Northwest region of the United States. It was first recorded in New Zealand around 1870, and first plantation was established at Whakarewarewa in 1905. As the second most important plantation species in New Zealand (currently 5% of planted area) (Cown, 1999), Douglas-fir has a history within the building industry as strong, stiff and stable lumber, ideal for structural applications. Traditionally it was sold as green lumber at a different size to radiata pine, which meant that a building was either using entirely Douglas-fir or using entirely radiata pine building but not a combination of both species. The sales of Douglas-fir dropped dramatically after the required treatment for structural lumber was introduced, because Douglas-fir is not easily treated and could not be combined easily with radiata pine in the building construction.

More recently another suite of regulatory changes NZS 3622, 3603 and, in particular, 3604 has introduced new timber grading standards. Timber now must be tested to ensure it has strength and stiffness performance suitable for structural applications. Comparing to radiata pine, Douglas-fir is proving to be stiffer and stronger based on facts well known by builders. However, it needs to be confirmed using more solid data that Douglas-fir should be separately and differentially regulated and, in particular, not inclusively with radiata pine (Karalus, 2007). On the other hand, the changes within the timber supply chain have led to increased opportunity for non-wood substitution. In order to maintain a presence in the traditional markets, more sophisticated description of product performance is being demanded (TIF, 2007).

1.2 Objectives of the project

Douglas-fir is a highly regarded and preferred timber for its superior strength, durability and decay resistance. Douglas-fir is also claimed to have more uniform properties and thus to be more stable compared to radiata pine. However, there is an apparent lack of detailed data on the wood properties of the New Zealand grown Douglas-fir (TIF, 2007). This project is designed to fill this gap with three objectives:

- To establish database of Douglas-fir fundamental properties related to stability.

- To compare these properties with those of radiate pine.
- To study the wood performance during kiln drying thus to increase the value by improved sawing and drying for both Douglas-fir and Radiata pine.

1.3 Literature review

Literature review was conducted to better understand the existing research in this area from which the factors affecting timber quality are identified and presented as follows.

1.3.1 Wood quality

Wood quality can be generally defined as a measure of the characteristics of wood that influence performance and values of products made from it. When people describe timber quality, they tend to mention the properties and characteristics which are undesirable. The timber should have no knots, no rot, no compression wood, no warp and so on – in other words, no defects. Briggs and Smith (cited in Bowyer *et al.*, 2002) put it differently, saying that "wood quality is measure of the aptness of wood for a given use.

The attitude of many sawmill industries could be summarised as 'more or less anything can be used as building timber'. Anything that is left over is used as building timber. It appears that the sawmill industry regards building timber as a bulk product and markets it as such.

The building industry's attitude can be summarised as 'timber should be cheap and good'. Many contractors assert that the quality of structural timber has steadily deteriorated in recent year. Excessive distortion is the main complaint. Consequently, market share has been lost to other materials.

1.3.2 Wood distortion

Wood distortion is a key quality issue for sawn timber. Distortion is a general term that is used to describe any deviation in a piece of timber from a plane surface. It includes four forms: twist, spring, cup and bow (see Figure 1-1).

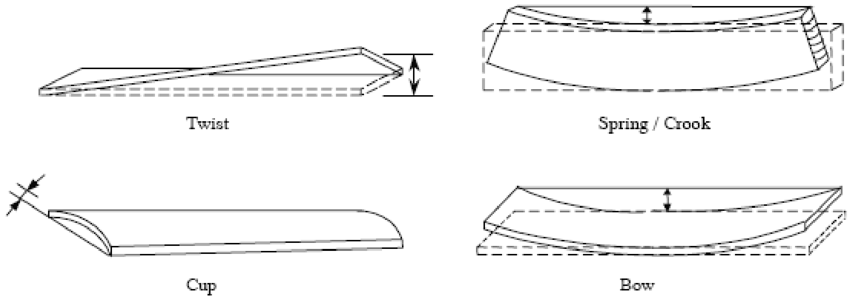


Figure 1-1: Various forms of distortion (Johansson *et al.*, 2004)

Spring or crook is the edgewise deviation of a piece of timber from a straight line from one end to the other, while bow is the flatwise deviation between the two ends. Twist is defined as the lengthwise spiral distortion which is generally related to a combination of large spiral grain and the anisotropic shrinkage variation in a piece of timber. Cup is the flatwise deviation from a straight line across the width of the board. For studs used in the building industry, twist is the mode of distortion that causes the most concerns. Spring (crook) also causes problems, while moderate bow can be tolerated. Cup is normally not a problem for structural timber, but it causes severe material losses during the subsequent planting after drying (Johansson *et al.*, 2004).

Among the wood properties, the intrinsic anisotropic shrinkage and its variation within a piece of sawn timber play an important role which is directly related to moisture content below the fibre saturation point. Wood distortion increases with decreasing of the moisture content.

1.3.3 Factors affecting the degree of timber distortion

<u>Anisotropic shrinkage</u>

Timber distortion can be caused by several different factors, but all types of distortion (twist, spring, bow and cup) can be attributed to non-uniform deformation when moisture content changes below the fibre saturation point. The wood commences shrinking at the fibre saturation point (Buchanan, 2002). Normally shrinkage in a direction tangential to the growth rings is the greatest and approximately twice that in the radial direction. The longitudinal shrinkage of normal wood is the least with a magnitude of 0.1 to 0.2 percent from green to over dry for most species and rarely exceeds 0.4 percent (Bowyer *et al.*, 2002). The shrinkage is normally described by:

$$\text{shrinkage} = \frac{\text{decrease in dimension or volume}}{\text{original dimension or volume in green}} \times 100\%$$

It is found that twist is mainly caused by a combination of shrinkage, annual ring curvature, and the spiral grain angle and its variation. Most of the occurrences of bow and spring can be explained by uneven distribution of longitudinal shrinkage within the sawn timber (Johansson *et al.*, 2006).

Cown (1999) reported that the average shrinkage values of Douglas-fir wood dried from green to oven-dry condition are 0.1% in the longitudinal direction, 3.5% and 6.5% in the radial and tangential directions, respectively. In the same report, the corresponding vales for radiata pine are 0.2%, 3.5% and 7.0%. Shrinkage varies both between trees and within a tree and such variation may also be affected by the size and shape of the sample, the density of the sample, the microfibril angle and the moisture content gradient while the sample is dried (Bowyer *et al.*, 2002).

Microfibril angles and fibre length

Shrinkage occurring perpendicular to the microfibril axis is several orders more than that along the fibre length, thus the anisotropic shrinkage in a piece of wood is significantly affected by fibril angle in dominating layer of secondary cell wall, the S2-layer (Dadswell, 1958; Anon, 1960; Voorhies and Blake, 1981; Krahmer, 1986). If the microfibril angles in the S2-layer were precisely parallel with the fibre axis, longitudinal shrinkage would be close to zero. However, there is always a small deviation of the microfibrils from parallelism which makes wood shrink in longitudinal direction.

Microfibril angles are inversely related to the fibre length, i.e. long fibres have small fibril angles and short fibres have large fibril angles (Panshin and de Zeeuw, 1980; Krahmer, 1986). Pedini (1990), in studying the tree height effect, found that the fibril angle decreased with increasing of stem height when the same ring numbers were compared. This study also confirms the relationship between fibre length and fibril angle. However, Saranpaa (1994) found that longitudinal shrinkage close to the pith increased with increasing height in the stem. The higher longitudinal shrinkage further up in the stem may be explained by a large amount of compression wood found at the top of the tree.

Compression wood

Compression wood is believed as an important cause of timber distortion. Compression wood is often denser and darker than the surrounding normal wood but it is not correspondingly strong and tough (Findlay 1975). The excessive longitudinal shrinkage of compression wood may cause the board to bend if one face of a board contains compression wood and the opposite face contains normal wood. In addition, the microfibril angle in the compression wood is much greater than that of normal wood. Compression wood behaves differently from normal wood with respect to physical and mechanical properties. Pronounced compression wood zone generally shrink more longitudinally and less transversely than normal wood during drying (Kollmann and Cote 1984). In a separate study, Hallock (1965) found that logs containing compression wood tended to spring and bow, whereas compression wood had insignificant effect on twist.

Spiral grain angle

Spiral grain refers to the alignment of tracheids at an angle to the stem axis. The direction of the spiral may be to the left or right of the apex of the tree as viewed and observer on the ground, and it is thus described as left or right spiral grain (Harris, 1989). Large spiral grain angle together with anisotropic shrinkage is found to be directly related to wood twist during drying (Stevens and Johnston, 1960). The general pattern is that spiral grain angle varies with age of the tree and its position along the trunk. Close to the pith, the grain angle is almost negligible, then by the second of third growth ring, the prevailing orientation is in the left direction. Krempl (1970) found that the correlation between the intensity of spiral grain and variables such as distance from pith, growth ring width and longitudinal position in the stem was very low, and there was a large variation between trees. Danborg (1994b) found a consistent positive correlation between growth rate and spiral grain angle. Cown *et al.* (1991) established spiral grain angle distribution patterns both in the radial and vertical directions in radiata pine trees. A general decrease in grain angle from pith to bark was found at all height levels in the stem. Grain angle increased in the stem height direction from base to top of the tree. Spiral grain levels are low in

Douglas-fir with no clear trend from pith to bark, a fact which contributes significantly to the very low levels of kiln drying degrade observed (Cown, 1999).

Corewood (Juvenile wood)

Corewood is defined as the wood near the pith of the tree and is characterized by progressive change in properties such as fibre length, fibril angle, density and strength. The wood towards the bark is called outerwood in which the properties are relatively constant thus the outerwood has well-developed structural patterns and stable physical behaviour (Bendtsen 1978). Usually the location of the boundary between the corewood and the outerwood is defined as the growth ring number from the pith from which the important properties start stabilizing outwards. In this project, the first 7 growth rings were defined as corewood for both Douglas-fir and radiate pine trees.

The fact that corewood proportion has an important effect on twist has been shown by Haslett *et al.* (1991), who studied the effect of log characteristics on distortion in young radiata pine. Milota (1992) studied Douglas-fir and found that the percentage corewood present in a board significantly affected twist. From this study, Milota (1992) proposed a criterion of timber pre-sorting based on log diameter and location of the board in the log. He also reported that the effect of the corewood on bow and crook was minimal.

Some characteristics of log may also contribute to the wood distortion which include log diameter and cross section shape. As these properties are not the objectives of this project, there will be no further discussion about their influence.

1.3.4 Influence of growth characteristics on timber distortion

Many researches have been carried out to analyse relationship between wood distortion and wood growth characteristics, however, it has proved difficult to obtain reliable relationships that can explain the wood distortion satisfactorily.

Knot

The major wood quality factor considered in most grading rules for sawn timber is knots. Fibre irregularities around the knots and compression wood on the underside of branches are properties known to affect distortion. However, studies on the relation between knots and distortion have not found any relationship of practical importance between the variables studied (Beard *et al.*,1993; Perstorper *et al.*, 1994).

<u>Growth rate</u>

Growth ring width has not showed significant correlation with distortion. However, the tendency for increased twist, spring and bow with increasing growth ring width was found by Mishiro and Booker (1988). This may be explained by the fact that growth rings in the region close to the pith are the widest where the spiral grain and longitudinal shrinkage are also the greatest.

<u>Wood density</u>

Contradictory results have been reported on the effect of wood density on distortion. Both Shelly *et al.* (1979) and Simpson *et al.* (1988) found that density slightly influenced spring but in the opposite trends. Shelly *et al.* reports that studs with density larger than the average value for the material studied exhibited nearly twice as much spring as studs less dense than the average. This is because of the larger shrinkage in heavier wood. However, Simpson *et al.* found that more spring occurs in lightweight boards than in heavier boards. The lightweight boards are supposed to contain a greater proportion of warp-prone corewood with large longitudinal shrinkage.

1.3.5 Influence of secondary processing factors on timber distortion

Two major processing factors affecting the timber distortion are sawing pattern and kiln drying. Firstly, with different sawing pattern, the shrinkage of timber in the board width and thickness directions is different, which results in one direction of the board shrinking more than another. Secondly, there may be corewood or transition wood on one side of the board, which shrinks more than the rest of the board; Uneven drying or over-drying may also result in more timber distortions (Denig, 1993).

<u>Timber sawing</u>

Sawing will influence both the productivity and the distortion of the sawn timber. As the wood progresses toward the centre of the log, the grade of the timber produced decreases due to the poor wood quality and variable properties (Denig, 1993). In sawn wood, the corewood (juvenile wood) has a major influence on the twist. This means that timber sawn close to the pith shows a greater twist than timber sawn away from the pith. Cupping increases with decreasing radius of growth ring curvature in the cross section of the timber. Therefore, timber sawn close to the pith or with pith enclosed exhibits a considerably larger number of visible defects than timber sawn away from the pith. Cracks during drying occur mainly on surfaces orientated to the pith, a fact that becomes clearer when the pith is on the surface.

Sandbergy (2005) studied the start-sawing of timber and found that with kiln drying, the star-sawn timber with a rectangular cross section has has a tendency of less bow and spring (crook) than those of timber sawn with traditional sawing patterns. It does not show any cup and has good shape stability according to the geometrical shape in the cross section. Since the star-sawing tends to have lower production yield, it is not widely accepted in New Zealand wood industry thus traditional sawing patters were used in this study as shown on Figure 1-2.

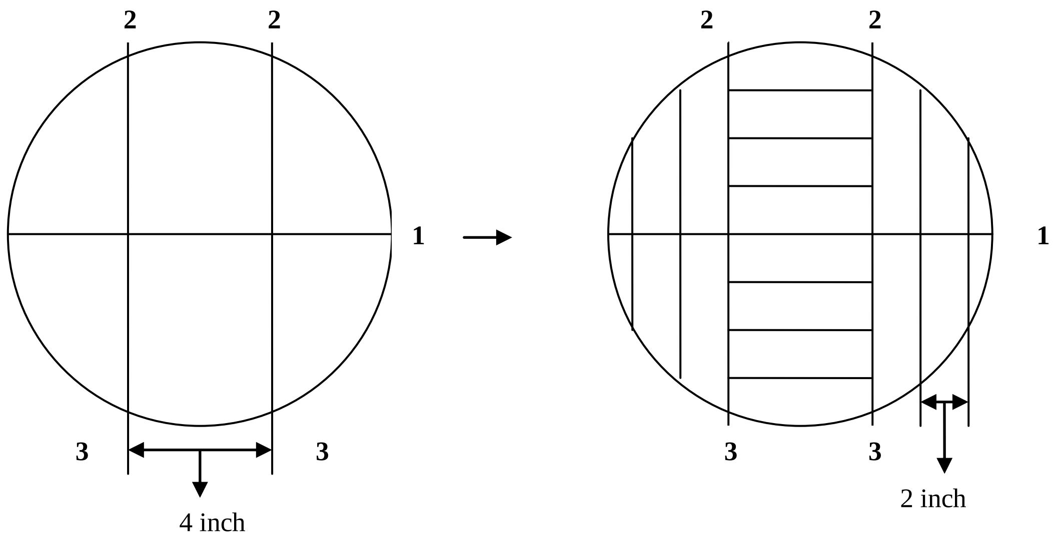


Figure 1-2: Sawing pattern used in this study

For the purpose of comparison of timber distortion difference, the timber was sawn purposely to show potential high distortion. In this way, log was firstly sawn into two halves, and break each half into three equally flitches by using a 4-inch widths twin edger. Then, the flitches are quarter-sawn into 2 inch thick timbers.

Timber drying

In kiln drying of timber, wood is dried at specified rates to minimise degrade (value loss). The dimensions of a board do not change when the moisture content (MC) is above the fibre saturation point (FSP) except for the case of a drying problem called "collapse". Below the FSP, however, substantial dimensional changes occur with MC changes due to the wood shrinkage. Changes in MC and MC gradient result in strain and strain-induced stresses, which my be sufficiently large to induce fracture or distortion as discussed above (Bousquet, 2000).

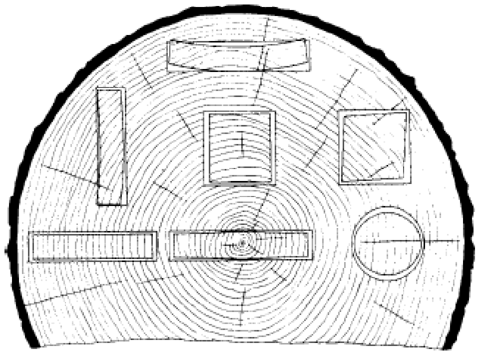


Figure 1-3: Characteristic shrinkage and distortion of plants, squares and rounds as affected by the direction of growth rings (Bousquet, 2000).

The directional variations in wood shrinkage and deformation are illustrated in Figure 1-3. To minimize directional variations in use, wood needs to be dry enough to match the service environment. Therefore, the key philosophy behind drying, as it is practiced today, is to control drying conditions so that distortion, and drying induced stresses and strains are controlled at minimum levels, which, in turn, will minimise degrade (Bousquet, 2000).

Although air drying was practised in early timber drying, controlled kiln drying is commonly used now in wood processing industry. Therefore in this project controlled kiln-drying will be used with practical drying schedules applied.

1.4 Knowledge gap

From the literature review, apparent knowledge gaps exist to achieve the goals of the project and these gaps are identified as follows:

- Lack of detailed data on wood physical and mechanical properties of New Zealand grown Douglas-fir.

- Limit information on wood stability performance and relationship beween the stability and wood properties of the New Zealand grown Doulas-fir.
- Limited information on the comparison in stability performance between the New Zealand grown Douglas-fir and radiata pine, the latter being the most popular species of plantation forests in New Zealand.
- Practical method to minimise the distortion of New Zealand grown Douglas-fir in secondary processing.

Chapter 2 Material and Method

This study was designed to investigate stability related basic wood properties and to determine stability performance of New Zealand grown Douglas-fir and radiata pine wood. In order to achieve these objectives, the experimental section of this project was divided into two parts. Part one was measurements of basic wood property using small clear samples which was conduced at the Wood Technology Lab of University of Canterbury. Part two investigated dimensional stability with full size timber boards which were performed at sawmill of Sutherland & Company Ltd. in Kaiapoi, near Christchurch.

2.1 Tree collection and sample preparation

In sample preparation, nine 60-year-old Douglas-fir trees and thirteen 26-year-old radiata pine trees were selected from forests of Selwyn Plantation Board Ltd., South Canterbury, New Zealand. After felling, all the stems were cut into 5.1m long logs. For the central-pith stems, 200mm long disks were removed between adjacent logs (see Figure 2-1). On average, four logs were cut off from each Douglas-fir stem and three logs were cut off from each radiata pine stem. Each log was marked on the large end side (LED) for its identification and corresponding discs were marked on the small end side (SED) of the disc. For example, log L1B is the bottom log cut from radiata pine tree No.1, disc S12D2 is the second disc from the stem bottom cut from Douglas-fir tree No.12. The 200mm long discs were then sent to the Wood Technology Lab at the University of Canterbury for small clear sample preparation whereas the logs were transferred to Sutherland & Company for full size timber study. The acoustic velocity of each log was measured after felling by using a resonance acoustic tool, Hitman®, to group the logs based on sonic classes for both species (**Radiata pine:** 2.69 - 3.84 ; **Douglas-fir:** 3.38 - 4.16). In addition, the acoustic test was to ensure that the logs collected fell in the normal range of each species.

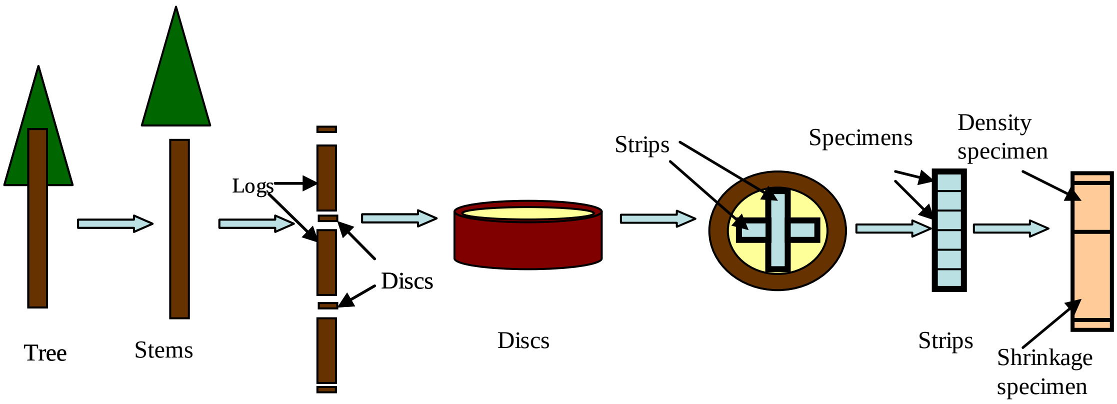


Figure 2-1: Samples preparation

2.1.1 Small clear wood sample preparation

From nine 60-year-old Douglas-fir trees and thirteen 26-year-old radiata pine trees, three centre-pithed Douglas-fir trees and seven centre-pithed radiata pine trees were selected to generate 13 Douglas-fir and 23 radiata pine wood discs of 200mm thick after felling. At the University of Canterbury, once all these discs were received, growth ring numbers and diameters of each disc were immediately recorded. The sawing lines were marked on both faces of the disc as Figure 2-2. Then, all the discs were stored into a cool room at 4^{o}C until further processing.

In the sample preparation, Douglas-fir disc S12D3 and radiata pine disc L2D2 were discarded since the existence of many visible knots. From the rest 44 discs, four 50mm-wide strips were first cut out from each disc through the pith along the directions of North-South and East-West, respectively (Figure 2-2).

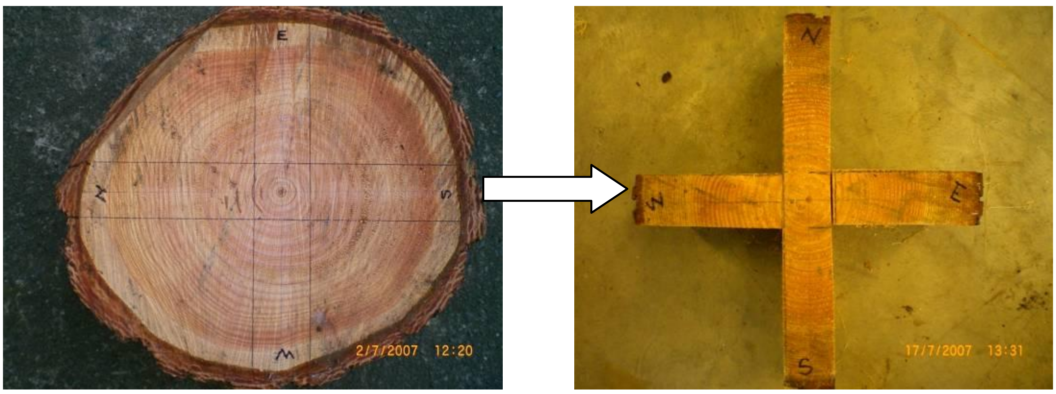


Figure 2-2: Marking of disc sawing and wood strip cutting

As shown in Figure 2-2, after four wood strips were cut from each disc, each strip was trimmed to 30mm in width direction and 150 mm in longitudinal direction. Then three of the four strips from each disc were cut along longitudinal direction into test samples of 20mm in thickness (radial direction) whereas the remaining strip from each disc was kept into plastic bag and stored in the cool room for further studies.. From one end of sample, a 30mm long piece was removed for measurements of green moisture content and density and the remaining 120mm sample was used for shrinkage and equilibrium moisture content measurements. In this way, totally 515 samples of 120×30×20mm (longitudinal × tangential × radial) were cut for measurement of wood stability properties including shrinkage and equilibrium moisture content, and 515 smaller specimens of 30×30×20mm were used for green moisture content and density measurements.

After the preparation of the sample, the identification (tree species, tree number, disc location in the stem) was recorded on the sample surface, e.g., L1D1N1 is the first sample cut close to the pith which trimmed from north wing strip of disc L1D1; S12D2S2 is the second sample cut close to the pith which was trimmed from south wing strip of disc S12D2. Then the average distance of the sample from the pith of the disc and the average growth ring number contained in each sample were determined. After the above procedures, all of the samples were stored in the cool room before measurement was taken.

2.1.2 Log sorting, sawing and grading for the large size boards

From the nine Douglas fir and thirteen radiata pine trees, thirty one Douglas-fir logs and thirty one radiata pine logs were cut out and sent to Sutherland & Company Ltd. for kiln drying tests. In order to determine the effect of corewood on timber distortion, small ends of each log were painted with different colours to identify the corewood (within 7th growth rings), outerwood (from 15th growth rings to the bark) and transition wood between these two categories as shown in Figure 2-3.

In order to ensure that the timber boards produced from each log can be tracked through sawing and kiln drying, the large end of each log was painted with a different colour pattern from the smaller end of the same log. The large end of each log was firstly painted with light colour flouro paint as background, and then another pattern was painted with dark colour flouro paint on top of its background pattern. The log's identification with information of its tree number and log height were also recorded accordingly. After this, the logs were cut by using the commercial sawing practice with nominal dimensions of 100mm $\times$ 50mm (4 by 2') with the sawing pattern shown in Figure 2-3.

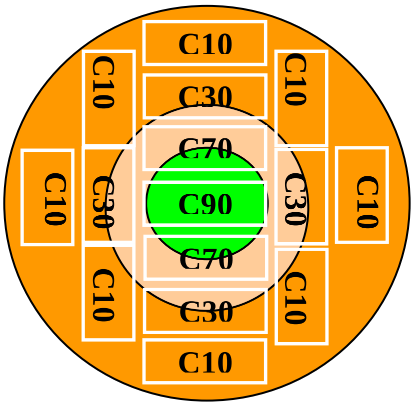


Figure 2-3: Sawing Pattern and colouring on the log end

Figure 2-4: Identification of full size timber

With the practical sawing, 210 Douglas-fir boards and 178 radiata pine boards were produced from the 31 radiata pine logs and 31 Douglas-fir logs. Each board was identified based on wood species (Douglas-fir or radiata pine), tree number, stem height and corewood proportion. This information was recorded on a piece of water proven tape which was stabled on the board end as shown in Figure 2-4 (corresponding to the large diameter log end). Since some of the sawn boards generated did not have full length or full thickness at the small diameter log end, only 202 Douglas-fir timbers and 158 radiata pine boards were used for the kiln drying tests. Many boards cut from outer part of the log contained some small proportion of transition wood or corewood while boards from the core part of the log contained a small proportion of transition wood or outerwood. Therefore, the boards were classified into four groups based on the proportion of corewood (CP, %) measured from the board end corresponding to the large diameter log end (see Table 2-1).

Table 2-1: Classification of timber by Corewood Proportion (CP)

Group	CP / %
C90	>90%
C70	60%～90%
C30	30%～60%
C10	<30%

The CP proportion was used later for distortion analysis. CP is defined as the ratio of corewood area to the whole end cross-section area. In this study, all sawn timbers were classified into four categories as shown in Table 2-2 which summarizes the CP distributions of both species.

Table 2-2: Summary of timber classification and test board numbers for full size timber (100mm×50mm×4.8mm)

Species	No. of Stems	No. of Logs	Numbers of timber				
			C90	C70	C30	C10	Sum
Douglas-fir	9	31	22	53	75	52	202
Radiata Pine	13	31	31	56	59	12	158

The 210 pieces of Douglas-fir timber and 158 pieces of radiata pine timber were also were visually graded (VGD) as VGD-1, VGD-2 and VGD-B following Australia/NZ visual grading standard (Standard, 1988). Boards of grade VGD-1 have the highest stiffness, followed by grade VGD-2 and the grade VGD-B. The boards falling into grade VGD-B should not be used as structural timber in practice.

2.2 Experiments on Basic Wood Properties

2.2.1 *Green moisture content and wood basic density*

From the sample preparation, 515 test specimens (204 for Douglas-fir and 311 for radiata pine) were used to determine green moisture content and wood basic density.

Dry-based moisture content (MC) is defined as the percentage of the water mass to the mass of moisture-free or oven-dry (OD) wood which can be expressed either as kg/kg or % (Bowyer, et al., 2002):

$$MC(\%) = \frac{\text{mass of water}}{\text{mass of oven - dried wood}} \times 100\%$$
$$= \frac{\text{mass of wet wood} - \text{mass of oven - dried wood}}{\text{mass of oven - dried wood}} \times 100\%$$

Wood basic density (ρ) is defined as the mass of oven-dry wood per unit of green volume (kg m^{-3}) (Bowyer, et al., 2002):

$$\rho = \frac{\text{mass of oven dry wood}}{\text{green volume}}$$

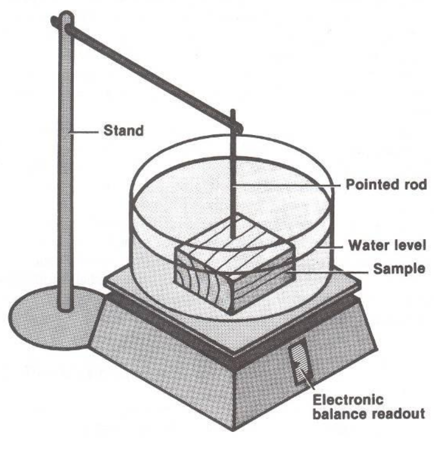


Figure 2-5: Determination of volume by displacement method (Bowyer, et al., 2002)

Mass of green wood was measured with a digital balance right after the samples were taken out of the cool room. Sample volume was determined by the displacement method (see Figure 2-5) before oven-drying. Oven-dry mass was measured after oven-drying of the samples at 103°C over 48 hours until no weight loss was detectible.

In the measurements of green moisture content and the wood basic density, the following equipments were used:

- Electronic balance:
  Range: 0-3000g
  Accuracy: 0.01g
- Beaker:
  Range: 0-500ml
- Oven:
  Pre-heat to 102^{o}C

2.2.2 *Shrinkage and equilibrium moisture content (EMC)*

515 samples (205 for Douglas-fir and 310 for radiata pine) from 30 wood discs were used prepared for measurements of shrinkage and equilibrium moisture content (EMC). EMC is the moisture content of wood when the wood sample is kept in an environment of constant temperature and relative humidity for sufficient long time. Fibre saturation point (FSP) is the moisture content at a point where all the liquid water in the lumen has been removed but the cell wall is still saturated with bound water.

Shrinkage is the reduction of wood dimensions in a specified direction or the reduction of wood volume that occurs when moisture is removed from cell wall. On the opposite, swelling is the reverse of shrinkage process when the wood absorbs moisture (Bowyer et al., 2002). Both shrinkage and swelling are expressed as percentage (%):

$$\text{shrinkage} = \frac{\text{decrease in dimensions or volume}}{\text{original dimension or volume}} \times 100\%$$

$$\text{swelling} = \frac{\text{increase in dimensions or volume}}{\text{original dimension or volume}} \times 100\%$$

In the shrinkage measurements, two measuring positions for each shrinkage sample were marked along the sample length on the four faces parallel with a ruler and colour pen with thin tip (see Figure 2-6). These marks ensured that the measurements of the sample thickness (in radial direction) and width (in tangential direction) at the same positions at different moisture contents. The radial and tangential dimensions were measured by a digital calliper. The longitudinal dimension was measured on a digital dial gage. Weight was measured by a digital balance.

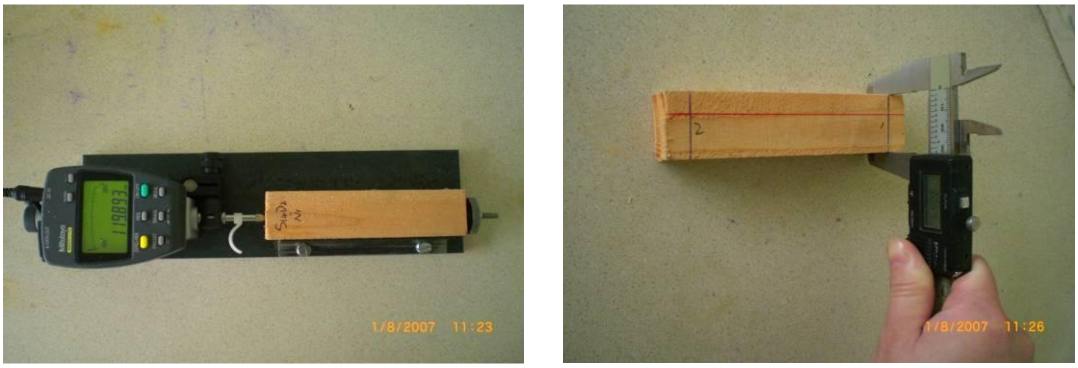


Figure 2-6: Measurement of shrinkage specimens

Once the samples were prepared and marked, the weight and dimensions for each sample were measured at green state. Then the samples were treated with anti-sapstain (Carbendazim, Oxine-Copper) to prevent stain growing during the experiment. After this, all of the samples were placed in a conditioning chamber which conditions were controlled at a temperature of 30℃ and relative humidity (RH) of 85% for initial equalisation. Once the sample weight change was not detectable, the RH was decreased in three steps from 85% to 65%, then to 50% and 40%, respectively.

In the first RH setting (85%RH), the sample weights were checked every day and it was found that two weeks were sufficient for the samples to reach a stable weight assuming equilibrium state was reached, thus in the following RH settings the equalization duration was controlled for two weeks. For each RH condition, once the equilibrium was reached, dimensions in three directions (longitudinal, radial and tangential) and weight were measured for calculation of the equilibrium moisture content (EMC) and shrinkage. A data logger was placed into the conditioning chamber with wood samples to record actual environmental conditions inside of the chamber. After the last step (lowest 40% RH), the samples were oven-dried at 103℃ for 24 hours to determine the oven-dry weight and dimensions.

After completion of the shrinkage measurements, all the shrinkage samples were again placed into the conditioning chamber with the set-up condition of 40% RH and 30°C to start the swelling measurement process. Increasing the RH of the conditioning chamber from 40% to 50%, 65% and 85% in three steps, the changes of the weight and dimensions of each sample were measured. In the measurements, the following equipments were used:

- Conditioning chamber (also called growth cabinet):
  Range of RH: 30~80%
- Data logger:
  Range: -30^{o}C ~+50^{o}C/ 0%~100%RH
  Accuracy: 0.2^{o}C / 3% RH
- Digital calliper:
  Range: 0.01 – 200 mm
  Accuracy: 0.01mm
- Digital balance:
  Range: 0-3000g
  Accuracy: 0.01g
- Digital dial gage:
  Range: 100mm~120mm
  Accuracy: 0.001mm
- Oven:
  Pre-heat to 103^{o}C

2.2.3 *Water resistant property*

After completion of the above wood property experiment, an additional test was conducted to determine water resistant property for both Douglas-fir and radiata pine. The water resistance property includes water absorption rate and water swelling rate which were determined as a function of elapsed time when the samples were immersed in the water bath. A temperature controlled water bath was set up in a lab in the Department of Chemical and Process Engineering, University of Canterbury (See Figure 2-7). The air temperature inside the chamber was controlled at 20 ^{o}C by two light bulbs and the water bath temperature was also controlled at 20^{o}C by temperature control thermistor.

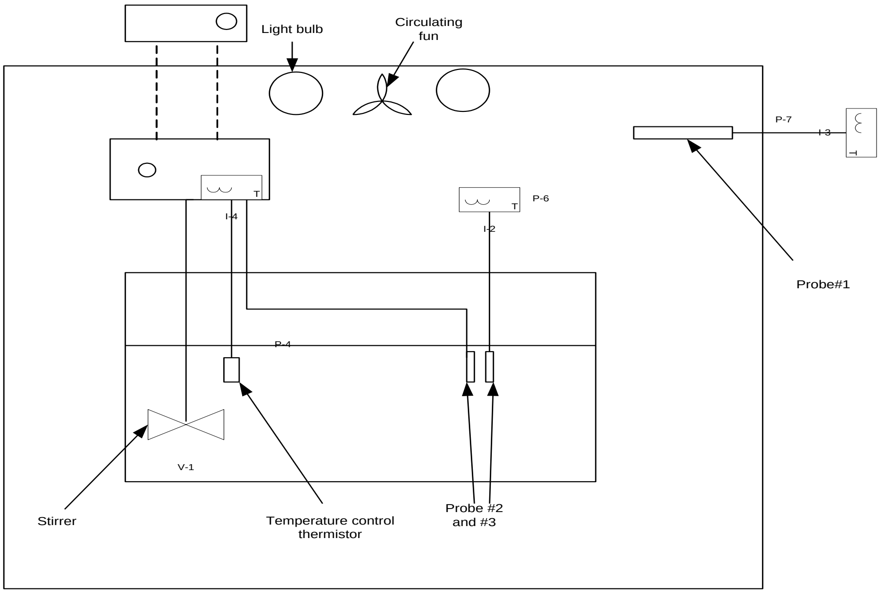


Figure 2-7: Temperature controlled water bath

In the water resistance property experiment, 48 shrinkage samples (120×30×20mm) in total were selected for both species and these samples were from discs of the same stem height of 5 meter, representing corewood and outerwood. On the 48 samples, 36 were used to measure water absorption rate and 12 were used for swelling rate in longitudinal, tangential and radial directions as shown in Table 2-3. In order to measure water absorption rate in a given direction (for example radial direction), four faces in parallel to this direction (two radial faces and two ends) were sealed thus leaving two faces (tangential faces) being exposed for water absorption. The sealant of Altex 421 Epoxy Timber Sealer was used before tests for the sealing. The 12 samples for water swelling rate tests were not sealed thus water could be absorbed through all directions.

Table 2-3: Samples collected at 5 m high position for water absorption rate test

	Corewood			Outerwood			
	Longitudinal	Tangential	Radial	Longitudinal	Tangential	Radial	Total
Douglas-fir	6	6	6	6	6	6	36
Radiata pine	6	6	6	6	6	6	36

In water absorption tests, the selected samples were firstly left in the room conditions for over two month to reach equilibrium. Weight was measured twice before and after the pre-sealing to determine the total mass change with the sealing. The samples were then placed into three stainless steel frames and immersed in the water bath at controlled temperature of 20 ^{o}C.

Weight was measured in each hour in first 2 hour period, then in every 6 hours during the following 12 hour period, and in every 12 hours in the next 4 day period. After this, the samples were weighed in each day in the final 83 days.

For the water swelling rate tests, 12 samples were placed into the water bath at the same time with water absorption samples. Dimensions were taken from each sample in 3 directions (longitudinal, tangential and radial) as the same time when the water absorption rate samples were weighed during the first 120 hours period. The following equipments were used in this experiment:

- Electronic balance:
  Range: 0-3000g
  Accuracy: 0.01g
- Temperature controlled water bath
  Temperature: 20 ^{o}C
  Dimensions: 45cm $\times$20cm $\times$20cm

2.3 Measurements of Full Size Timber Distortion

2.3.1 Measurement before timber drying

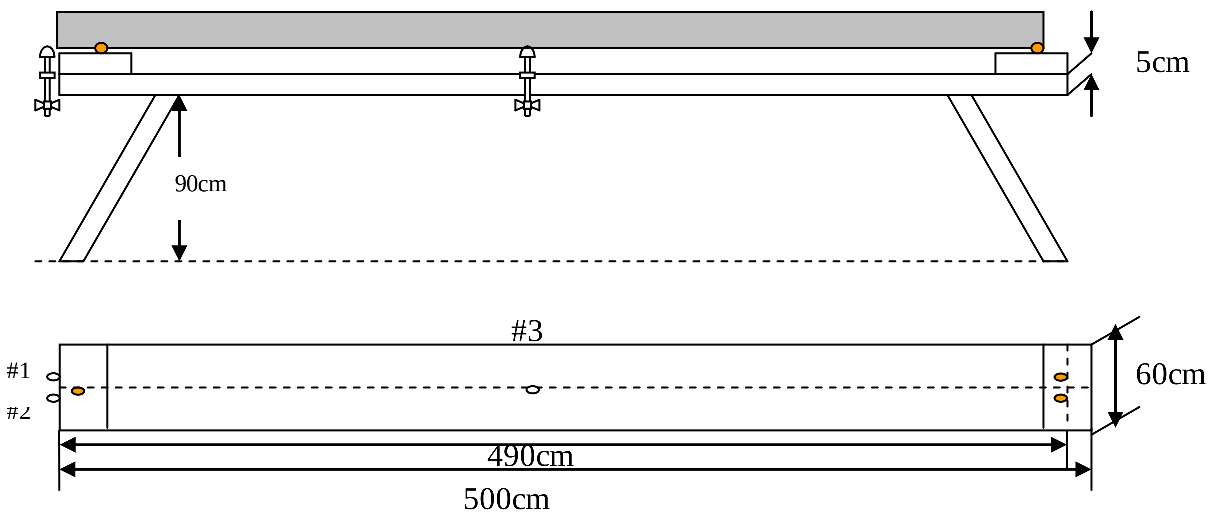


Figure 2-8: A bench made for timber distortion measurement

For measurements of distortion and dimensional changes of the full size timber at sawmill, a measurement bench was designed and built as shown in Figure 2-8. 385 pieces of full size boards of 50 mm × 100 mm × 4.9 m were used for sawmill studies. The measurement of weight, dimension and acoustic velocity was taken from each board before and after kiln drying.

After sawing, the green boards were visually graded by technical staff of sawmill. Then board dimensions of width and thickness were measured at 3 marked positions along the board length with digital calliper and length was measured with a tape ruler. Weight was measured with digital balance and acoustic velocity was measured with Hitman (Director HM200). Green moisture content of Douglas-fir timber was also measured by using a capacitance type of moisture content meter. However, the green moisture content of radiata pine was unable to be obtained as its values were out of the meter's measurement range. In the sawmill studies, the following equipments were used:

- Electronic balance:
  Range: 0-30kg
  Accuracy: 0.01kg
- Digital calliper:
  Range: 0.01 – 200 mm
  Accuracy: 0.01mm
- L601-3 moisture meter
  Range: 0-30%
  Accuracy: 0.01
- Acoustic tool: Director HM200
- Tape ruler
  Range: 0-7 meter

2.3.2 Measurement after timber drying

After the initial grading and measurements, the green boards of Douglas-fir and radiata pine were stacked in two separate packs using commercial practice (sticker and sticker spacing). Then both stacks were dried in the same charge in a commercial kiln with the drying schedule of dry-bulb temperature of 75℃ and wet-bulb temperature of 60℃ for 20 hours. In this period of drying, Douglas-fir boards were dried from an average MC of 33.3% to an average MC of 18.4%. As the final MC of radiata pine boards was much higher than Douglas-fir boards and it was unevenly distribution, all radiata pine boards were moved to a dehumidification kiln and seasoned for additional two more days. After this, all timbers of Douglas-fir and radiata pine were equalized in a covered area for 7 days before the further measurements were taken.

Figure 2-9: Measurement of distortion

After the equalization of kiln-dried timbers, dimensions (width, thickness, length) and weight of each board were measured. MC was measured with moisture meter and acoustic velocity was measured with Hitman. Board distortions (bow, spring and twist) were also determined at the same time. Spring was measured with the board laying flat on the measuring table and bow was measured with the board lying with edge contacting the measuring table. In this way, board weight had minimum effect on its distortion.

2.3.3 Estimate of the board stiffness

Acoustic MOE is the dynamic measure of a material's stiffness and is often used as an estimate of the static MOE of the board (Wang, 2005). The acoustic MOE (GPa) of each board was determined before and after drying from the following equation (Wang, 2005; Grabianowski, 2006; Bucur,2006):

$$\mathrm{MOE} = \rho \times V^2$$

Where ρ (kg/m^3) is the wood basic density of the board and V (m/s) is the measured acoustic velocity. Further analysis of the relationships between acoustic properties and corewood proportion of board will be discussed in Chapters 5 and 6.

Chapter 3 Physical and Stability Properties of Douglas-fir

Douglas-fir is New Zealand's second most important plantation species with a reputation for producing excellent quality structural timber. In order to prove the stability benefits of New Zealand grown Douglas-fir, some basic wood properties such as green moisture content, basic density and shrinkage were studied and the results are presented in this chapter.

3.1 Green moisture content and basic density

3.1.1 Appearance of wood discs and green moisture content

Three centre-pithed Douglas-fir trees were selected to generate 13 wood discs for small samples preparation. Average diameter of each Douglas-fir disc was measured before the small clear wood samples were prepared and growth rings of the disc (the average value of counted ring number from bottom disc of each tree in four different directions) were counted. The diameter profile of the disc diameter along the tree height is illustrated in Figure 3-1 for Tree S12, Tree S13 and Tree S14. As tree S12 had the smallest diameter of 321.5mm for the butt disc with the average growth rings being 46, the outerwood samples were unable to be prepared. The butt log diameters for Tree S13 and Tree S14 were similar with values of 443.5mm and 497mm, respectively, with corresponding average growth rings for these two trees being 61 and 62.

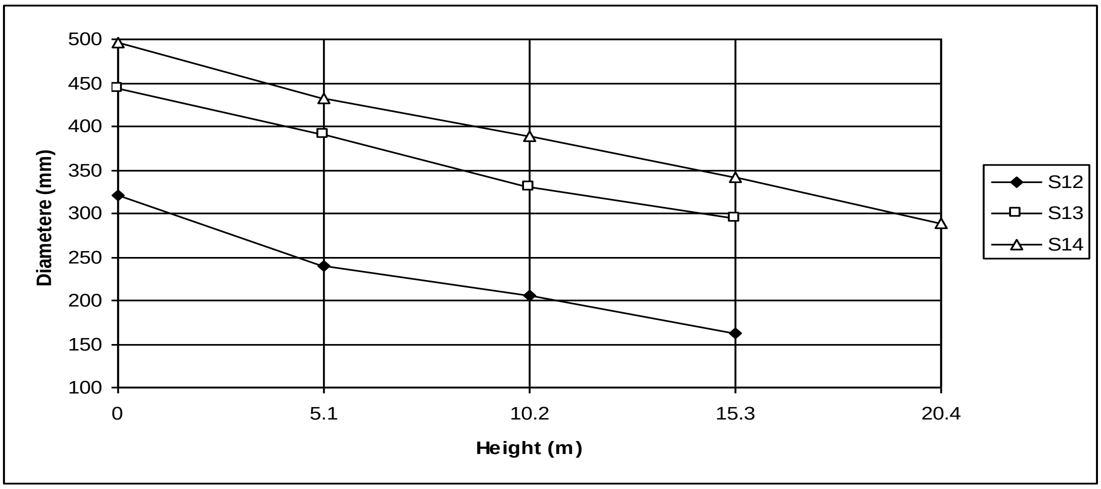


Figure 3-1: Diameter distribution of three Douglas-fir trees along the tree heights

Table 3-1: Summary of green moisture content (MC) of Douglas-fir trees

Tree ID	S12	S13	S14	Overall
Mean MC (%)	44.91	61.04	55.26	55.70
Standard Deviation (%)	3.03	27.39	27.55	25.74
Minimum MC (%)	39.48	37.45	35.52	35.52
Maximum MC (%)	55.42	123.88	133.26	133.26
No. of samples	32	73	99	204

The results of green moisture contents measured from the small clear samples of Douglas-fir are summarised in Table 3-1. In total, 204 samples were prepared from the above three trees (Tree S12, Tree S13 and Tree S14). The measured green moisture content ranged from 35.52% to 133.26% (Table 3-1). Due to the cutting and storing of the small samples in the cool room, the small samples could lose some moisture which was indicated by low values of moisture content (about 50%) detected from some sapwood samples of tree S12. However, as the fibre saturation point of Douglas-fir is around 27% at room temperature, the moisture loss was unlikely to affect the shrinkage results. The overall mean value of the green moisture content was 55.7% and the mean value between trees ranged from 44.91% to 61.04%.

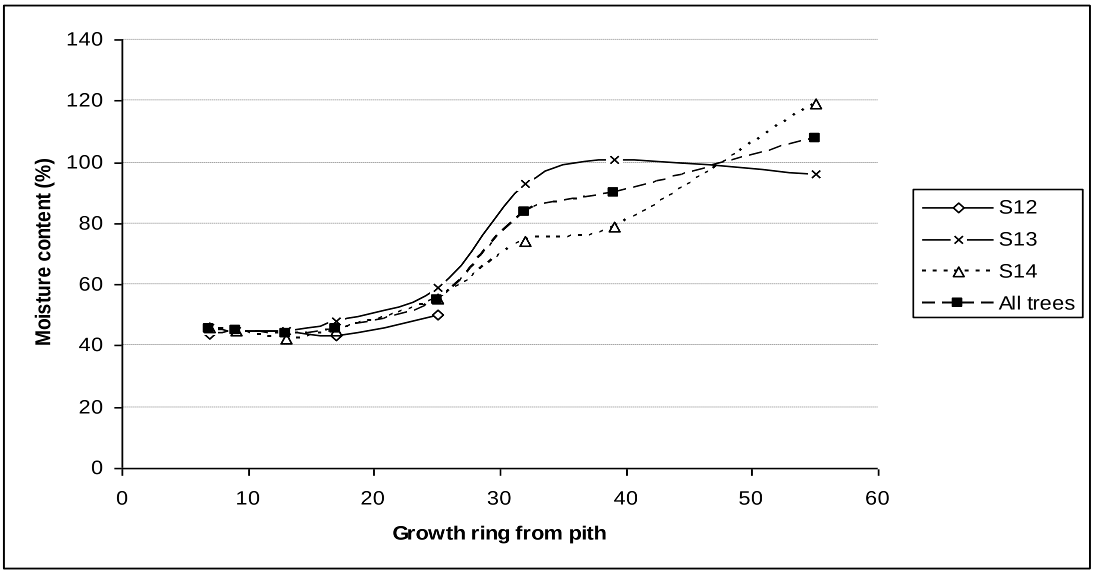


Figure 3-2: Radial profile of green moisture content of Douglas-fir

The profile of green moisture content along the radial direction is shown in Figure 3-2 for the three trees. From this radial profile, the difference between sapwood and heartwood can be clearly observed. The heartwood was found in the first 25 rings from the pith with average green moisture content being fairly constant at around 45%. Then the average green moisture content increased to a range of 75% to 85% at heartwood/sapwood boundary (25^{th} to 30^{th} growth rings). It is interesting to note that the sapwood moisture content for Tree S14 is relatively stable varying between 95% and 100%, but the green moisture content for Tree S13 varied from 75% at the heartwood/sapwood boundary to 120% near the bark. Since comparatively smaller butt disc diameter and less growth ring were found in Tree S12 (as mentioned in Figure 3-1), the variation of its green moisture content was present to 25^{th} growth rings.

In this study, the average heartwood green moisture content of Douglas-fir samples was 44.8% which was close to the value (45%) reported by Walker (2006). However, the average sapwood green moisture content of 80.7% measured in this study was much lower than the previously reported value of 145% (Walker, 2006). Reason of this difference can be due to site difference and the moisture loss during the sample preparation and storing. It was also mentioned in unpublished report by Turner (2007) that NZ Douglas-fir from south island showed comparative lower green MC than those from north.

3.1.2 Basic density

Wood density is one of the most important wood properties affecting lumber strength and stiffness. Basic density of Douglas fir was measured from the above 204 small clear wood samples. The results in Table 3-2 show that the overall basic density ranged from 339.03 to 681.33 kg m^{-3} with the mean value of 446.06 kg m^{-3} and standard deviation of 56.32 kg m^{-3}. The mean basic density for different trees ranged from 404.92 kg m^{-3} for Tree S12 to 473.73 kg m^{-3} for Tree S13. The average outerwood (from 15^{th} growth ring and outward) density was 468 kg m^{-3} which was slightly higher than the values of 450 kg m^{-3} reported in literature (Bowyer *et al.*, 2002; Cown, 1999).

Table 3-2: Summary of wood basic density (kg m^{-3}) of Douglas-fir trees

Tree ID	S12	S13	S14	Overall
Mean	404.92	473.73	438.96	446.06
Standard Deviation	33.88	58.81	49.93	56.32
Minimum	348.36	351.05	339.03	339.03
Maximum	470.46	676.83	681.33	681.33
No. of samples	32	73	99	204

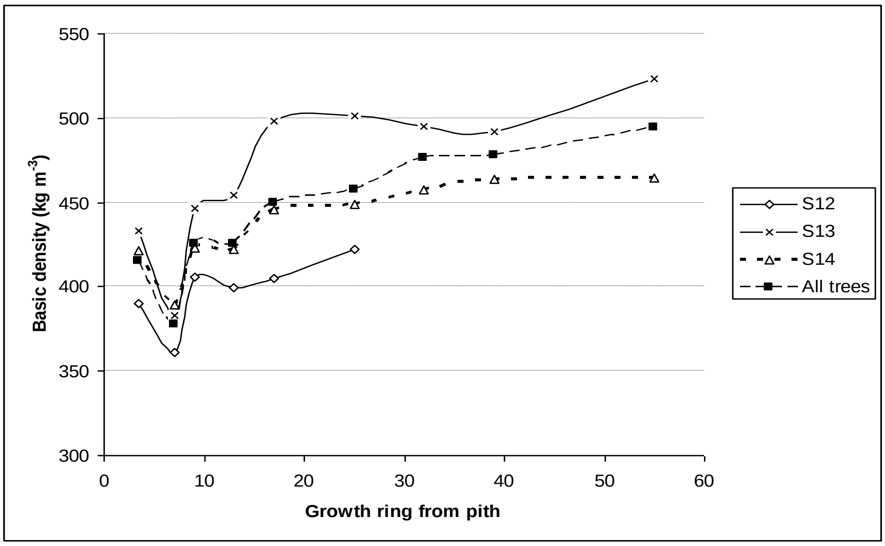


Figure 3-3: Density profile of Douglas fir samples in radial direction

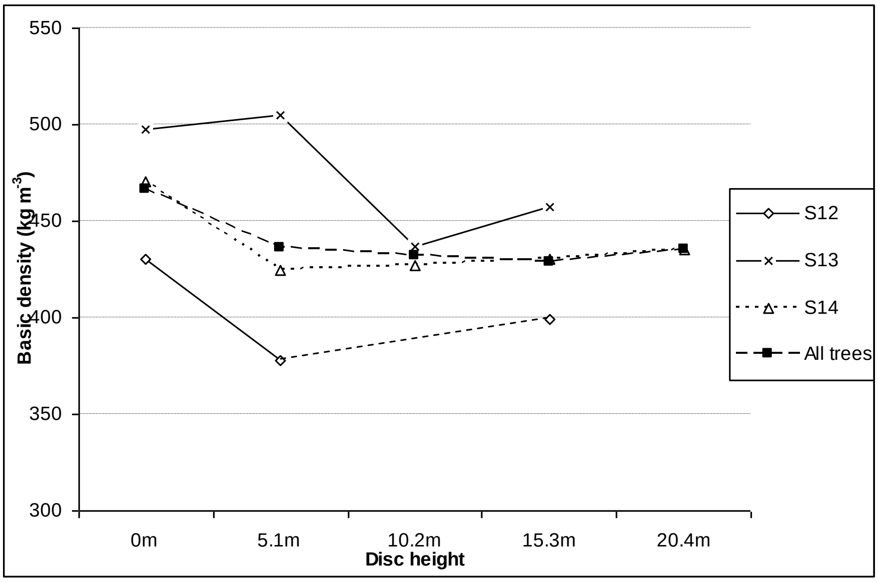


Figure 3-4: Density profile of Douglas-fir in vertical direction

Profile of the wood basic density both along the radial and tree height directions are shown in Figure 3-3 and Figure 3-4, from which significant variation can be observed within a stem and between stems. In the disc radial direction, the average basic density was low near the pith and its lowest value was found around the 8^{th} growth ring, then it increased towards the bark. Such variations were likely to be due to the silviculture operation like thinning. Similar variation trend was also found by Megraw (1986) who found that the average basic density firstly decreased outward from pith, levelled off after 8 or 10 rings and then gradually increased with increasing the ring number. The high density values in Douglas-fir near the pith are the result of high earlywood content in this region. As the specimen size in this study was normally larger than a single ring band, earlywood/latewood proportion and distribution within Douglas-fir stem were unable to separate.

In the first 10 growth rings, Tree S13 and Tree S14 had similar density variation and values which were higher than that of Tree S12. However, the density of Tree S13 became much higher than other two trees from the 11^{th} growth ring outwards. From the measured results (Figure 3-2, Figure 3-3), no clear correlation was found between the green moisture content and the wood basic density.

In the tree height (longitudinal) direction (Figure 3-4), the overall average wood density tended to be highest within the butt discs (466 kg m^{-3}), and then decreased along the tree height although the variation above 5.1m was not remarkable. However, the highest density for Tree S13 was found to be at 5.1 m high from the ground. Wood disc of Tree S12 at 10.2m position was rejected during the sample preparation since too many visible knots were found in this disc, therefore, its density data was missing at this height in Figure 3-4. The overall trend of wood basic density along the tree height, in general, is consistent with findings of Cown (1999).

3.2 Shrinkage and swelling

The wood shrinkage and swelling are closely related to wood microstructure, wood chemistry and vary with anisotropic directions (radial, tangential and longitudinal) (Walker, 2006). Wood shrinks and swells much less in the longitudinal, or fibre axis direction, than in the cross grain direction (Megraw, 1986).

3.2.1 Shrinkage variation

This section will present the variation trend of averaged shrinkages along the radial direction and the tree height. The shrinkage of the Douglas-fir was measured from 205 small clear wood samples as described in Chapter 2 and the averaged shrinkage from green to oven-dry over 3 trees are shown in Figure 3- 5 as a function of growth ring. It is found that both tangential and radial shrinkage appeared to be higher in the sapwood than in the heartwood while longitudinal shrinkage tended to decrease from pith to bark.

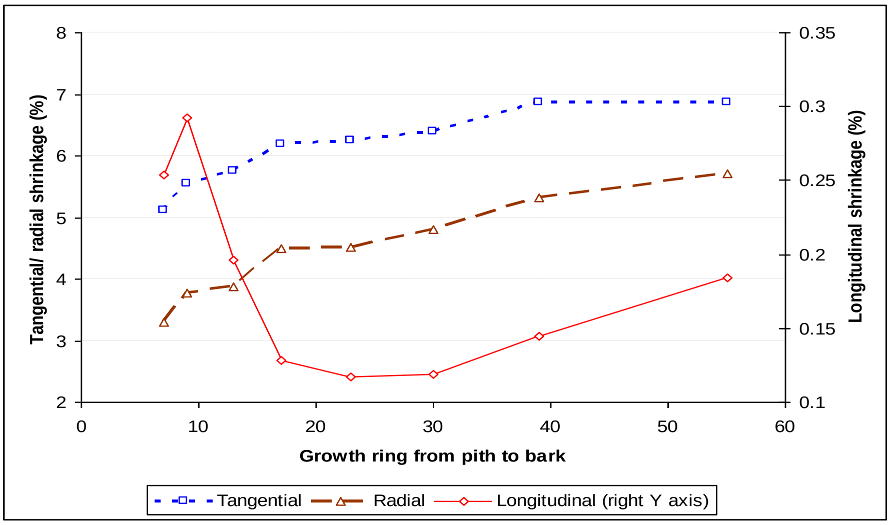


Figure 3-5: Shrinkage profile of Douglas-fir along the disc radius

Table 3-3: Directional shrinkage values for New Zealand grown Douglas-fir

	Green MC (%)	Shrinkage from green to oven-dried (%)				Shrinkage from green to 12% MC (%)		
		L	*T*	*R*	*Vol*	*L*	*T*	*R*
Mean	58.81	0.20	6.05	4.15	10.12	0.12	2.97	1.78
Standard Deviation	29.14	0.17	1.15	1.02	1.83	0.15	0.72	0.68
Minimum	36.39	0.01	2.92	1.37	5.93	0.00	0.67	0.29
Maximum	150.15	1.34	9.84	7.04	15.81	0.98	5.13	4.62

Table 3-2 gives the summarised results of overall shrinkage both for green-to-oven dry and for green-to-12% moisture content. From this study, it is found that the mean shrinkage of Douglas-fir in longitudinal, tangential and radial directions from green to oven dry were 0.2%, 6.05% and 4.15%, respectively, while the corresponding shrinkage from green to 12% moisture content were 0.12%, 2.97% and 1.78%. In a similar study by Cown (1999), the longitudinal, tangential and radial shrinkage from green to 12% moisture content were reported to be 0.1%, 3.5% and 1.8% which were close to the results from this study. However, the directional shrinkage for the New Zealand grown Douglas-fir is comparatively lower than reported values of Douglas-fir grown in Europe and North America. Walker (2006) reported that the tangential and radial shrinkage values from green to 12% moisture content were 4.0% and 2.5% for UK Douglas-fir and similar shrinkage values from green to 12% moisture content (4.1% for tangential and 2.3% for radial) were given by Canadian Wood Council (CWC, 2009) for the North American grown Douglas-fir.

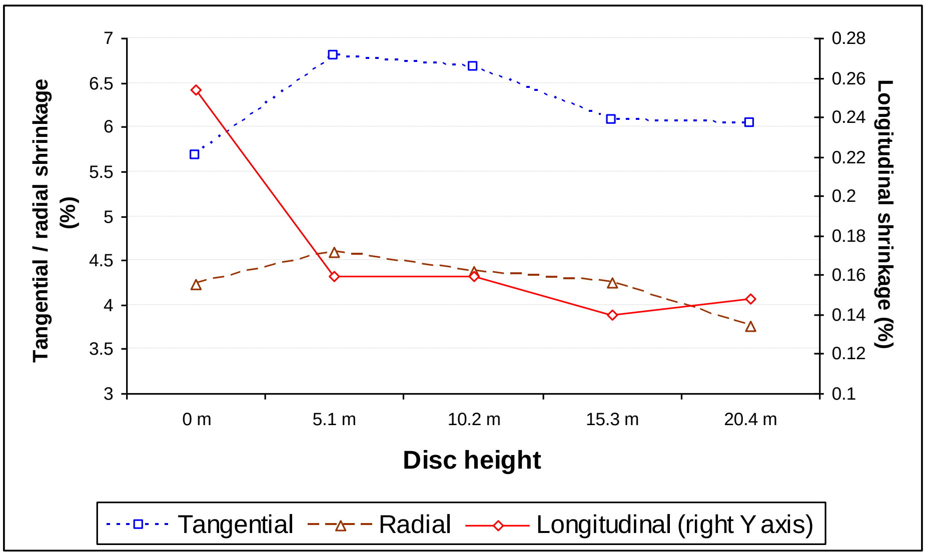


Figure 3-6: Shrinkage profile of Douglas-fir along the stem height

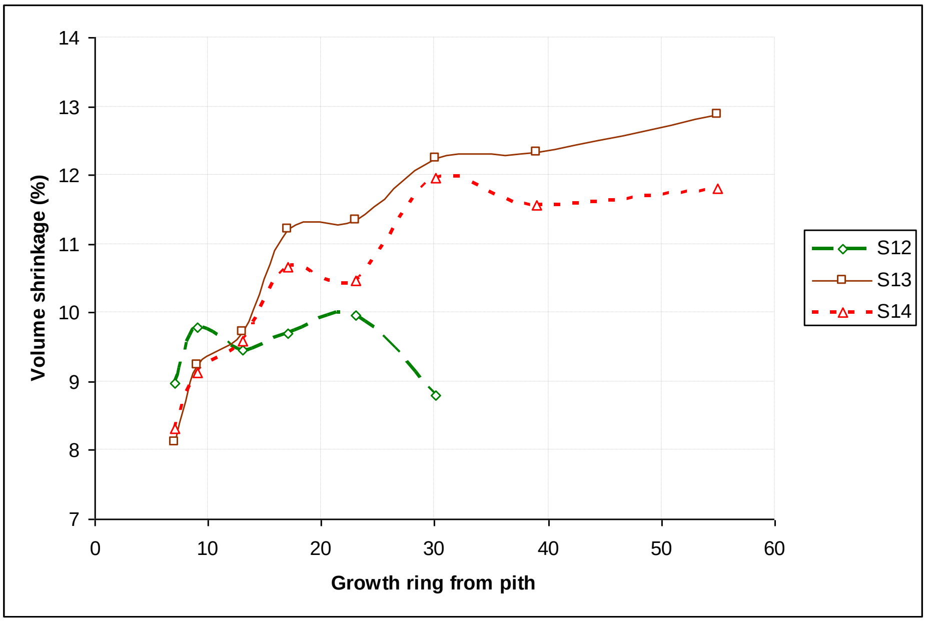


Figure 3-7: Variation of volumetric shrinkage between trees

Figure 3- 6 shows that average shrinkage from green-to-oven dry as a function of tree height. For the tangential and radial shrinkage, the highest values were observed at 5.1m high and decreased upwards from that height. The tangential and radial shrinkage in the butt discs was slightly lower than the highest values. However, the highest longitudinal shrinkage was measured at the butt discs and became fairly constant between 0.14% and 0.16% for wood above 5.1 m.

Figure 3 – 7 shows the volume shrinkage variation along the disc radius in different trees. Although a general trend of volume shrinkage increasing with the growth ring number from pith to bark, Tree S12 shows a low value at the 30th growth ring of 9% which is much lower than the corresponding value at the same growth ring for other two trees (12%). The overall volume shrinkage value was measured to be 10.16% which was lower than the value of 11% reported by Cown (1999) and that of 10.9% by Schroeder (1972).

Figure 3-8 illustrates the variation of anisotropic shrinkage of Tree S14 as a function of its radial and vertical position within stem. It can be seen that the variation of shrinkage (longitudinal, tangential and radial) follows similar trend to that previously discussed in Figure 3-5. In all heights, the highest longitudinal shrinkage value was found near pith. This value tended to be consistently stable between 0~0.2% after the 15th growth ring. The overall value of tangential and radial shrinkage shows an increasing tendency from pith to bark. The influence of tree heights on shrinkage values was not clearly described.

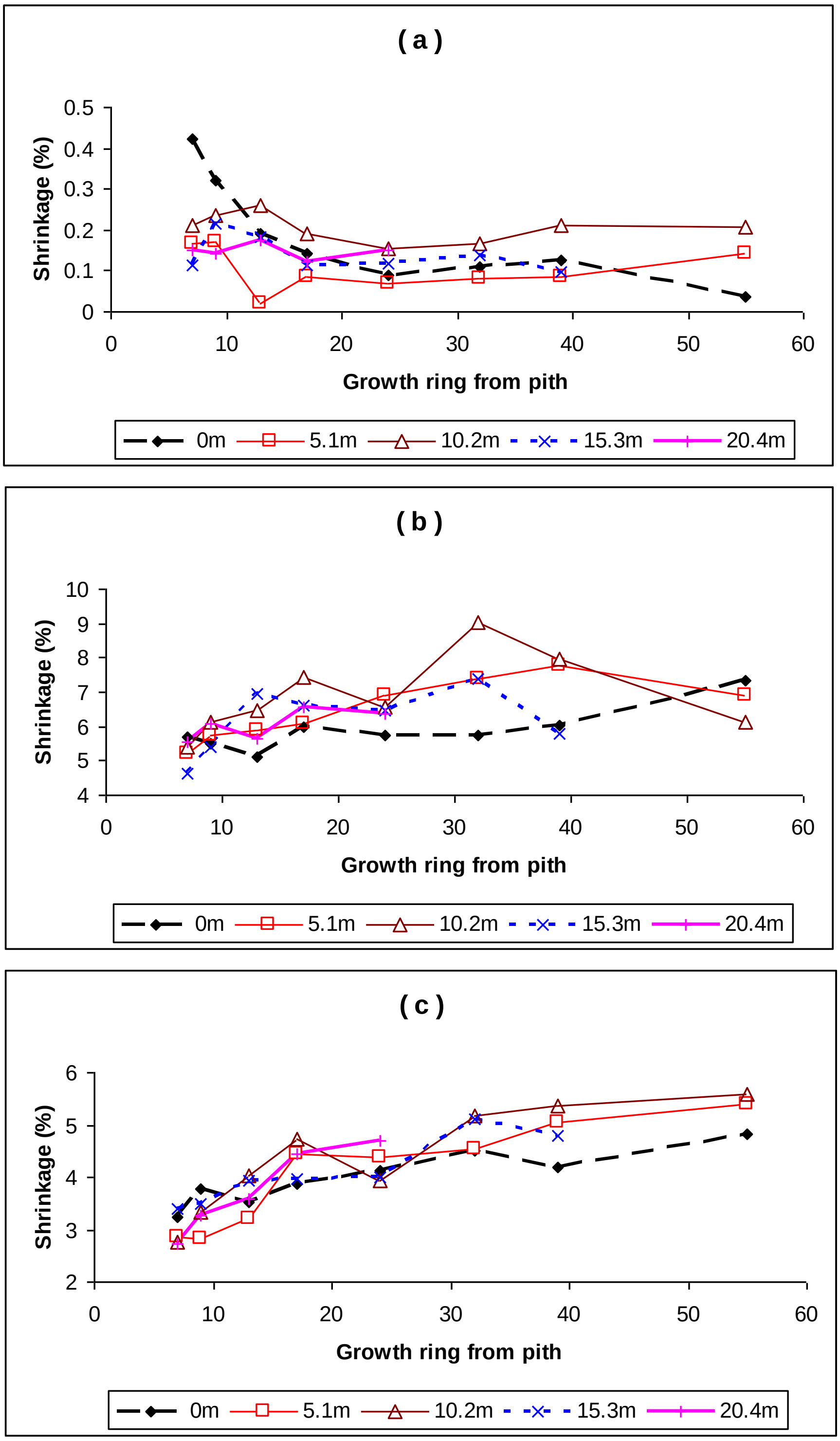


Figure 3-8: Variation of oven-dry shrinkage for Tree S14, (a) longitudinal, (b) tangential and (c) radial

3.2.2 Longitudinal shrinkage

Longitudinal shrinkage can be taken as an indicator of timber distortion and it is also related to microfibril angle of wood (Nault, 1989), therefore, this section will discuss particularly on the longitudinal shrinkage. For most species, the longitudinal shrinkage from green to oven dry condition is only 0.1% to 0.2% and rarely exceeds 0.4% (Bowyer et al., 2002). The longitudinal shrinkage is typically higher in core wood (also called juvenile wood) of a tree and decreases along the radial direction until mature wood is reached in the stem (Nault, 1989).

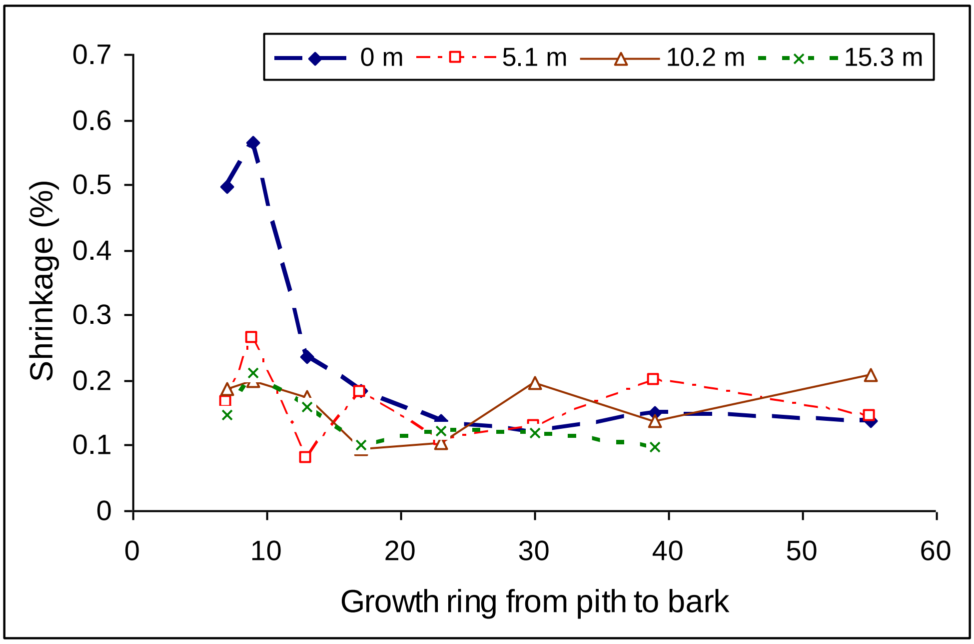


Figure 3-9: Longitudinal shrinkage of Douglas-fir averaged over three trees

From this study, except for the bottom disc, variation of the longitudinal shrinkage for Douglas-fir is not generally wide as shown in Figure 3-9 which shows the average longitudinal shrinkage over the three trees. The effect of the tree height is also indicated by each line. The average longitudinal shrinkage for Douglas-fir samples was less than 0.3%, and more than 80% of the samples were between 0.1% and 0.2%. As the highest microfibril angle value is found in the wood close to ground and near the pith of a tree, the bottom disc has the highest longitudinal shrinkage in the corewood with values from 0.2% to 0.6%. This indicates that the timber cut from the bottom log may tend to be distortion prong due to the high longitudinal shrinkage and the shrinkage gradient. However, this was not supported by the lumber sawing trials. No significant warp propensity was discovered for Douglas-fir butt logs from full-sized timber results which will be discussed in Chapter 5.

3.2.3 Directional swelling with moisture absorption

When wood undergoes moisture absorption process (also called wetting), it swells. In this study, the dimensional swelling of Douglas fir in longitudinal, tangential and radial directions, respectively, was determined from oven dry to four different RH conditions (40%RH, 50%RH, 65%RH and 85%RH) at 30°C. The variation of the average swelling as a function of equilibrium moisture content (EMC) is shown in Figure 3-10.

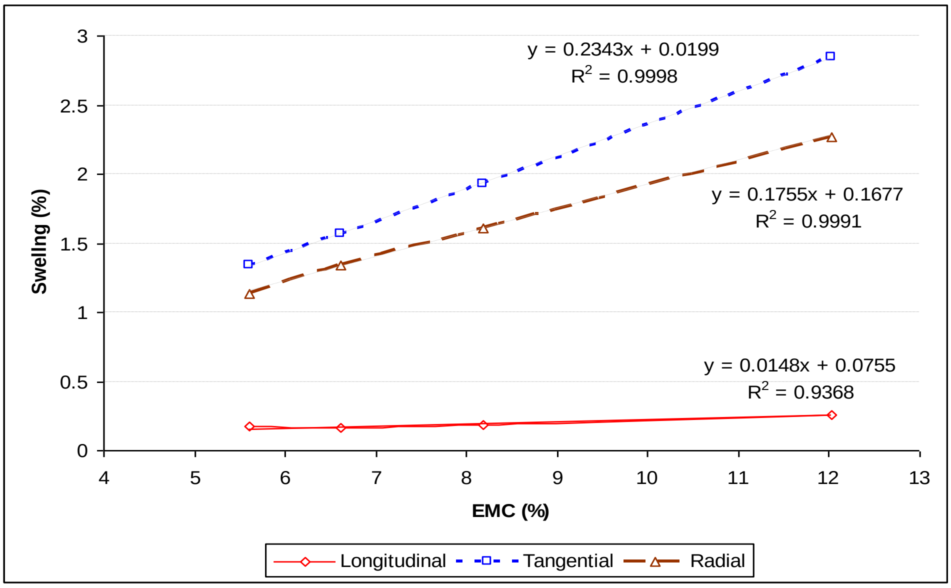


Figure 3-10: Swelling profile of Douglas-fir at different EMC

Similar to the trend of shrinkage variations, the average swelling of the Douglas fir samples was the greatest in tangential direction and the least in longitudinal direction. For moisture content below 15% (in Figure 3 - 10), a significant positive linear relationship was drawn between the dimensional swelling and the moisture content, most obviously in tangential and radial directions. Therefore, it is possible to use these linear correlations to calculate the wood swelling at known increase in the moisture content.

3.3 Equilibrium moisture content and fibre saturation point

3.3.1 Equilibrium moisture content

A piece of wood with given moisture content will loss moisture when it is placed in drier conditions but it gains moisture when placed in more humid conditions. The process of moisture loss to the environment is called desorption, and the moisture gain is called adsorption (Tsoumis, 1991). In this study, equilibrium moisture content of New Zealand grown Douglas fir was measured at four different relative humidities

(RH) (40%RH, 50%RH, 65%RH and 85%RH) at a temperature of 30°C, both for absorption and desorption. The results of the measured moisture sorption isotherms at 30 °C were illustrated in Figure 3 – 11. The EMC values of the Douglas-fir samples during desorption at a constant temperature of 30 °C and RH of 40%, 50%, 65% and 85%, were 8.1%, 9.2%, 11.9% and 17.1%, respectively. The corresponding values during absorption were 5.6%, 6.6%, 8.2% and 12%.

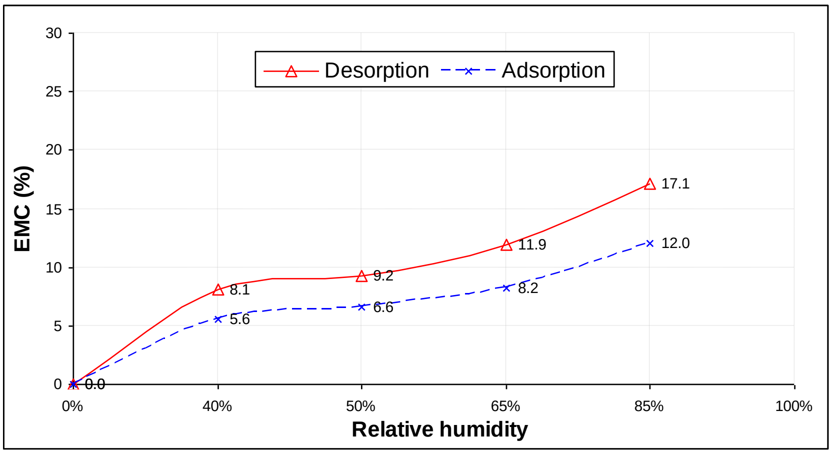


Figure 3-11: Moisture sorption isotherms of Douglas-fir at 30°C

The sorption isotherms of New Zealand Douglas-fir followed a characteristic sigmoid curve. The EMC value during desorption was higher than for adsorption with 2-5% MC difference which is termed as hysteresis. This difference increased with the increasing of relative humidity. For example, at 65% RH, the equilibrium moisture content of wood during desorption is 11.9%, whereas the same wood going from dry to wet would have an equilibrium moisture content of 8.2%. This difference of 3.7% can make a major difference in mechanical properties of the wood. The EMC of desorption obtained at 40% RH in this study was higher than values reported by Tsoumis (1991) and Bramhall (1976) but values at other RH conditions were similar to the reported values. It is assumed that the data of Tsoumis and Bramhall was the averaged values over desorption and absorption.

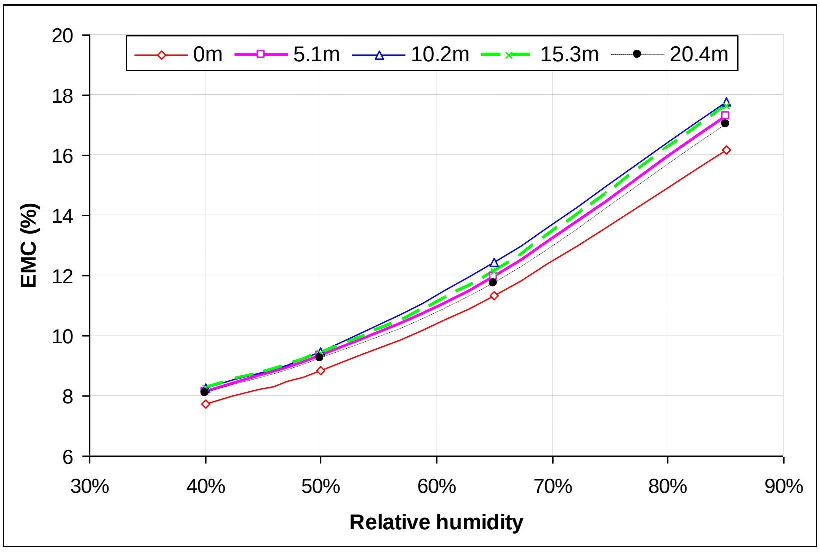


Figure 3-12: EMC variation of Douglas-fir in vertical position

Figure 3-12 shows the average values of EMC during desorption at different humidities in which the effects of tree height is also indicated by different fitted curves. It is interesting to note that the samples from the bottom disc showed much lower EMC value than those from other stem heights. However, no significant correlation was found between the wood EMC and stem height except for the consistent low EMC value for the bottom discs.

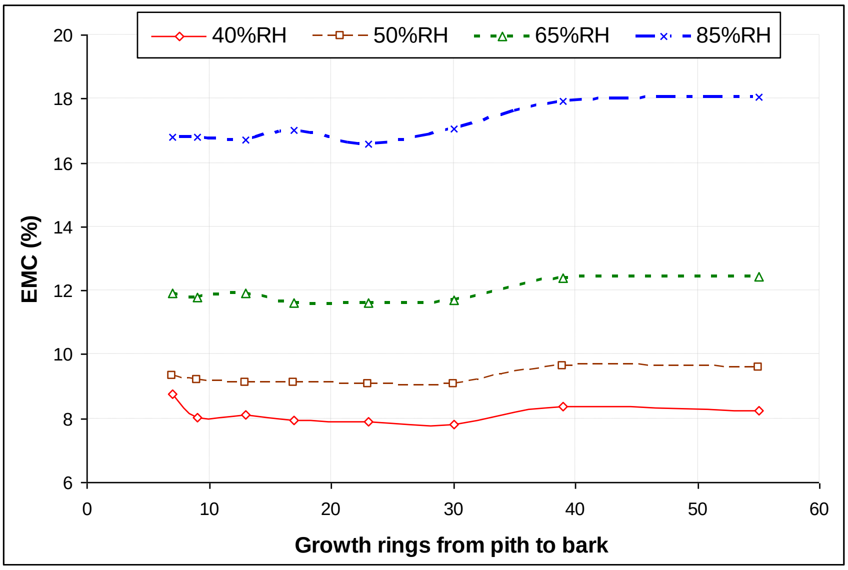


Figure 3-13: EMC variation of Douglas-fir along the disc radius

The EMC distribution along the disc radius was illustrated in Figure 3-13, showing that sapwood from 30^{th} growth ring outward tend to have higher EMC values than the heartwood at a given RH. This difference was more obvious at higher RH conditions of 65% and 85%. At 85% RH, the average EMC value of the outer wood was about 18% while the value for the core wood was only 16.7%.

3.3.2 Fibre saturation point

There are different definitions for the wood fibre saturation point (FSP) although it was firstly introduced by Stamm (1964) who stated that the FSP is the moisture content when the cell wall is fully saturated with bound water but the lumens are free of any liquid water. The FSP was later found to be a critical point when most physical and mechanical properties start to change with moisture content below this point. As moisture is removed below the FSP, the wood starts to shrink (Rowell, 2005). In this study, two methods were used to determine the FSP. In the first method, the FSP was determined from the correlation plot of the tangential shrinkage against the moisture content. As shown on Figure 3-14, the FSP is the MC value at the intersection point of tangential shrinkage line with the vertical axis.

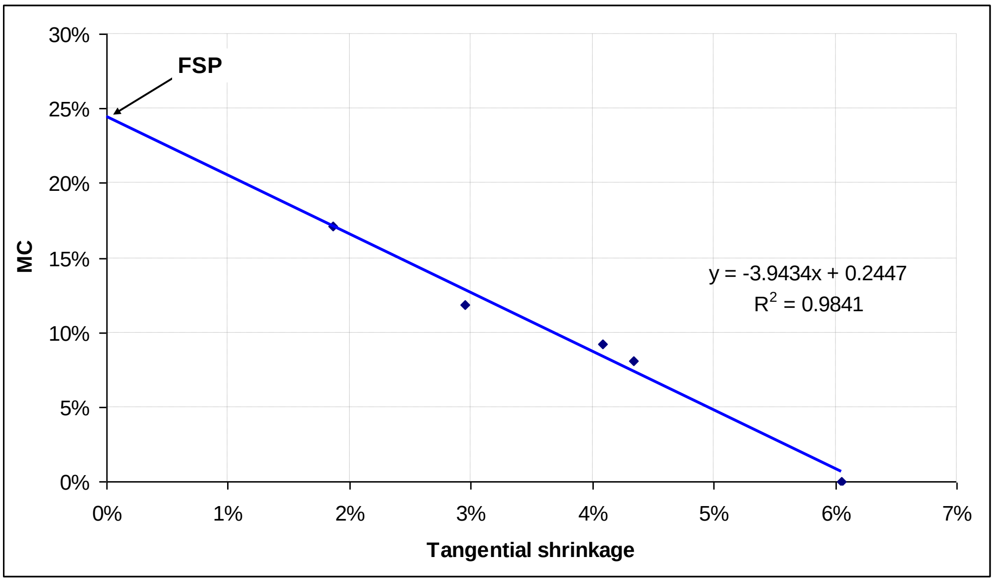


Figure 3-14: Determination of FSP from the linear relationship of tangential shrinkage and MC

In this way, the average FSP of 24.47% MC for New Zealand grown Douglas fir at 30^{o}C was determined from the above linear relationship. This value was lower than the reported value of 27% at room temperature (at 20°C) in Timber Design Guide (Miller, 1999). This could be due to two factors, one being the wood variability and second being the effect of temperature. It was noted by Stamm that FSP decreased 1%

for each 10°C increased in temperature between 0°C and 100°C (Skaar, 1988). According this method, the FSP at 20°C for the samples in this study should be 25.47% which is closer to the reported value of 27%.

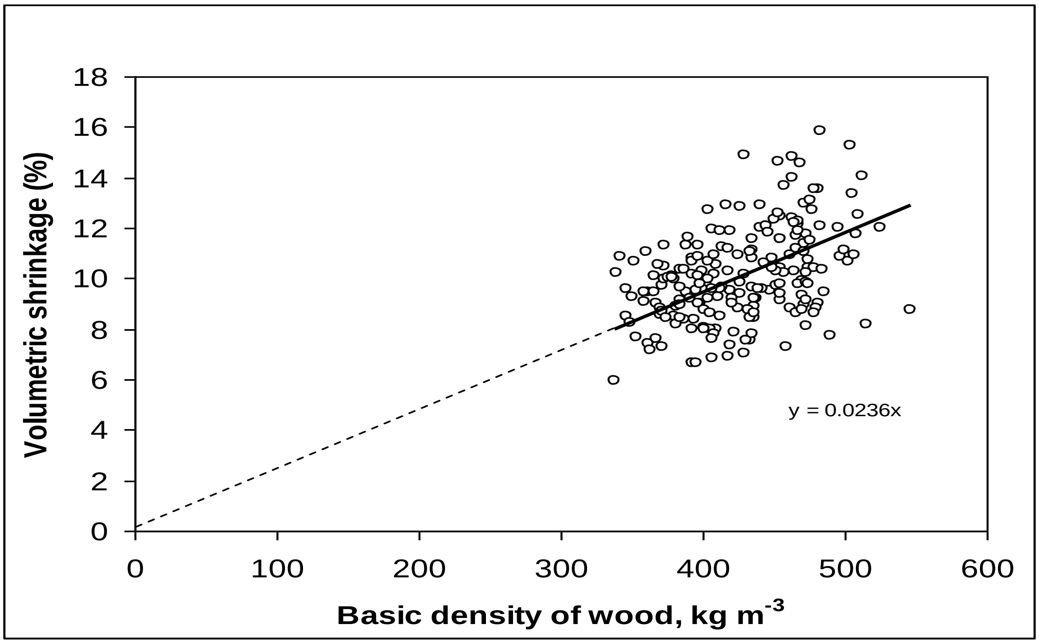


Figure 3-15: Determination of FSP from the relationship of volumetric shrinkage and basic density

Another method for determination of FSP was introduced by Walker (2006) who related the FSP to volumetric shrinkage from green to oven dry:

$$\boxed{\text{Volumetric shrinkage (\%)} = \text{MC at fibre saturation (\%)} \times \text{basic density} \times 10^{-3}} \quad (1)$$

This method reflects the effect of wood basic density which varies significantly among samples. A correlation between the volumetric shrinkage and the wood basic density may be fitted from the experimental data as shown in Figure 3-14. In this way the FSP can be determined as the slope of volumetric shrinkage against the wood basic density as shown in Figure 3-15. However, the FSP found in this was (23.6%) is even lower than the value found from the tangential shrinkage as shown in Figure 3-14. In addition, the scattering data between the volumetric shrinkage and the wood basic density would induce greater experimental errors as observed in Figure 3-15 (Skaar, 1988, Walker, 2006). Therefore, the FSP values determined from the tangential shrinkage method are presented in this thesis.

Table 3-4: FSP variation within tree

Height	FSP (%)	R^2
0m	25.51	0.9824
5.1m	24.95	0.9903
10.2m	23.65	0.9738
15.3m	23.52	0.9728
20.4m	23.67	0.9844

Table 3-5: FSP variation between trees

Tree	Density (kg m^{-3})	FSP (%)	R^2
S12	404.92	26.76	0.9745
S13	473.73	24.44	0.9867
S14	438.96	24.1	0.983

Table 3-4 and Table 3-5 show the FSP variation within a tree and between trees. Table 3-4 presents the average FSP values at different tree heights from which it is found that the FSP decreases with the stem height, however, the FSP values tends to remain at a constant value of 23.6% above 10.2m. FSP also varies considerably between trees as seen from Table 3-5. Tree S12 has the highest value of 26.67% which is about 2% higher than other two trees. Vorreiter (1963) reported that FSP decreased with increasing wood density but no clear correlation was found between the wood basic density and FSP in this study due to the scattering data.

3.4 Water resistant properties

3.4.1 Water absorption property

After completion of basic wood property experiments, water resistant property experiment was conducted for the selected 36 samples used above, 12 samples for each of longitudinal, tangential and radial direction. Figure 3-16 presents the results from the water resistant experiment at a controlled water temperature of 20^{o}C. The total water immersion period was 2000 hours as shown in x-axis in Figure 3-16. The vertical (y) axis illustrates the water intake by wood samples from uncoated surfaces per square centimetre.

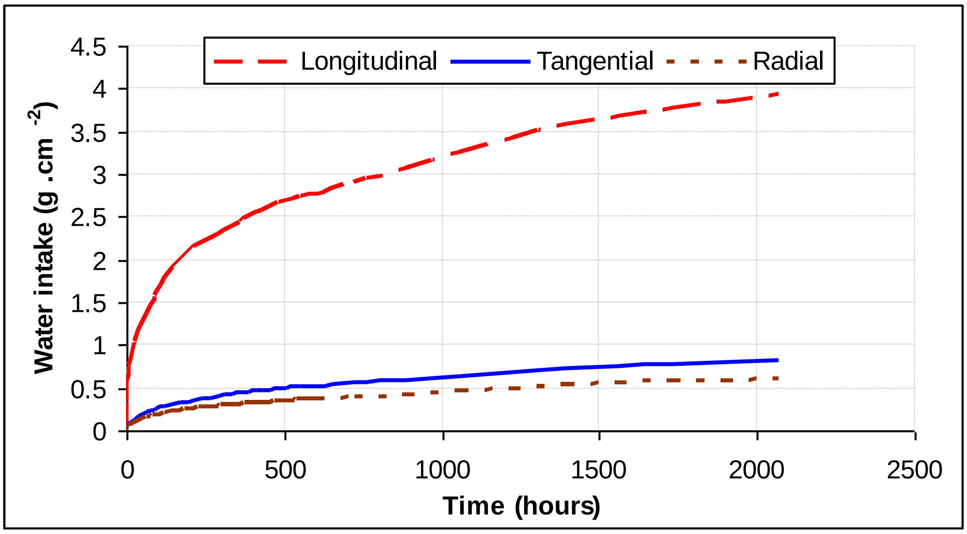


Figure 3-16: Water absorption of Douglas-fir in water bath, at 20°C

The result shows the water absorption rates increased rapidly in the first 2 hours, and then gradually reached the maximal values. It can be seen very clearly that the Douglas fir sample tends to have much higher water absorption capability in the longitudinal direction than tangential and radial directions. This can be expected as the primary structure of soft wood, the longitudinal tracheids provide more open free-flowing channels for the water absorption whereas the water has to penetrate into the cell walls in both tangential and radial directions once the bordered pits were aspirated.

Furthermore, the water absorption behaviour in the outerwood and corewood was investigated and the results are shown in Figure 3-17. It was found that outerwood tends to have higher water absorption capability in the water immersion than corewood in longitudinal direction and tangential direction. However, this distinction was not found in radial direction. Being the most important part of translocation and storage of food in tree growing, the outerwood was showing more active than corewood and had more open pits in a living tree thus, once dried, some pits are still open or partially open.

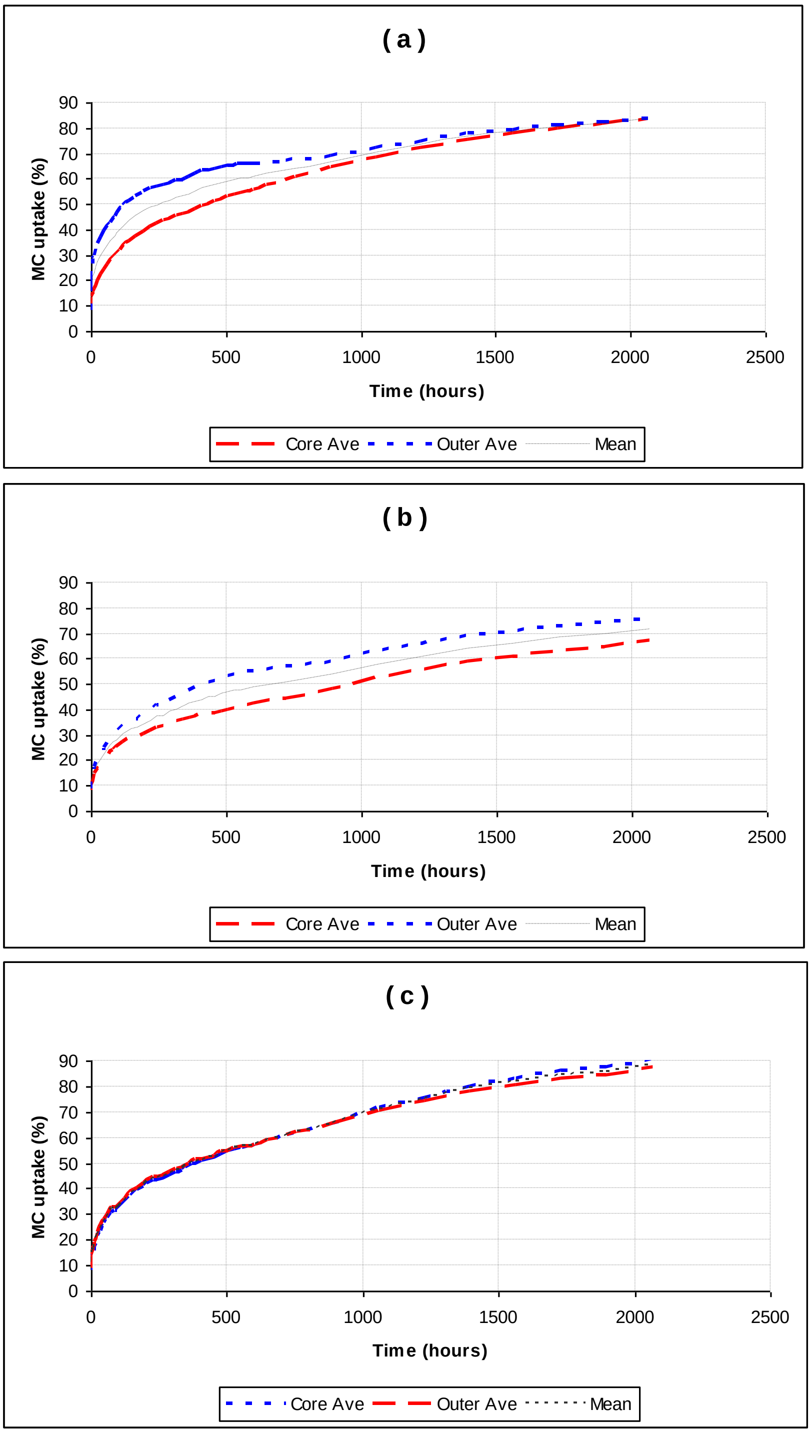


Figure 3-17: Comparison of moisture absorption between core wood and outer wood, (a) longitudinal, (b) tangential and (c) radial directions

3.4.2 Water swelling variation

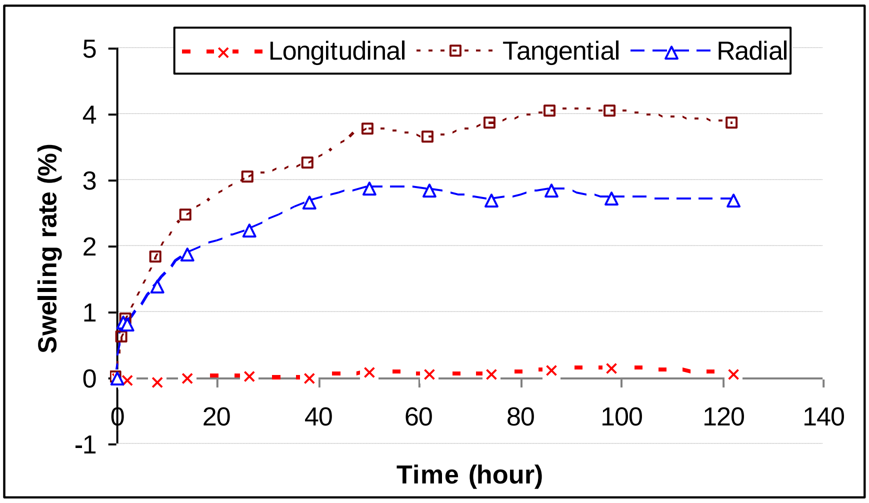


Figure 3-18: Swelling profile of Douglas-fir in water bath, at 20°C

Figure 3-18 shows the anisotropic swelling of the Douglas fir samples from which it can be seen that the tangential and radial swelling increased rapidly in the first 2 hours, and then gradually reached their maximum values. It is also noticed that the swelling in the tangential direction is the highest followed by the radial direction and the swell in longitudinal direction is the lowest, similarly to the wood swelling under humid conditions. However, the longitudinal swelling (0.1%) was relatively constant with the immersion time. The longitudinal swelling data also shows negative value which may be due to the experimental errors, however, this phenomenon was also observed in separate studies (Hann, 1969).

Figure 3 - 19 compares the swelling between core wood and outer wood in the three anisotropic directions. From the results of tangential and radial swelling, the required immersion time for the samples to reach equilibrium was over 48 hours. It is most interesting to find that the outer wood tended to swell more in tangential and radial directions, while it showed lower longitudinal swelling than the core wood. The reason for this can be a combined effect of water absorption in the water immersion and wood intrinsic properties and microstructure. The outer wood absorbed more water in the water immersion thus tends to swell more than the core wood, however, the core wood has higher microfibril angle thus the core wood showed higher longitudinal swelling. This may also explain why the longitudinal swelling varied in a

narrow range during the water immersion. The maximum swelling in tangential and radial direction for Douglas-fir was around 4% and 3 %, respectively.

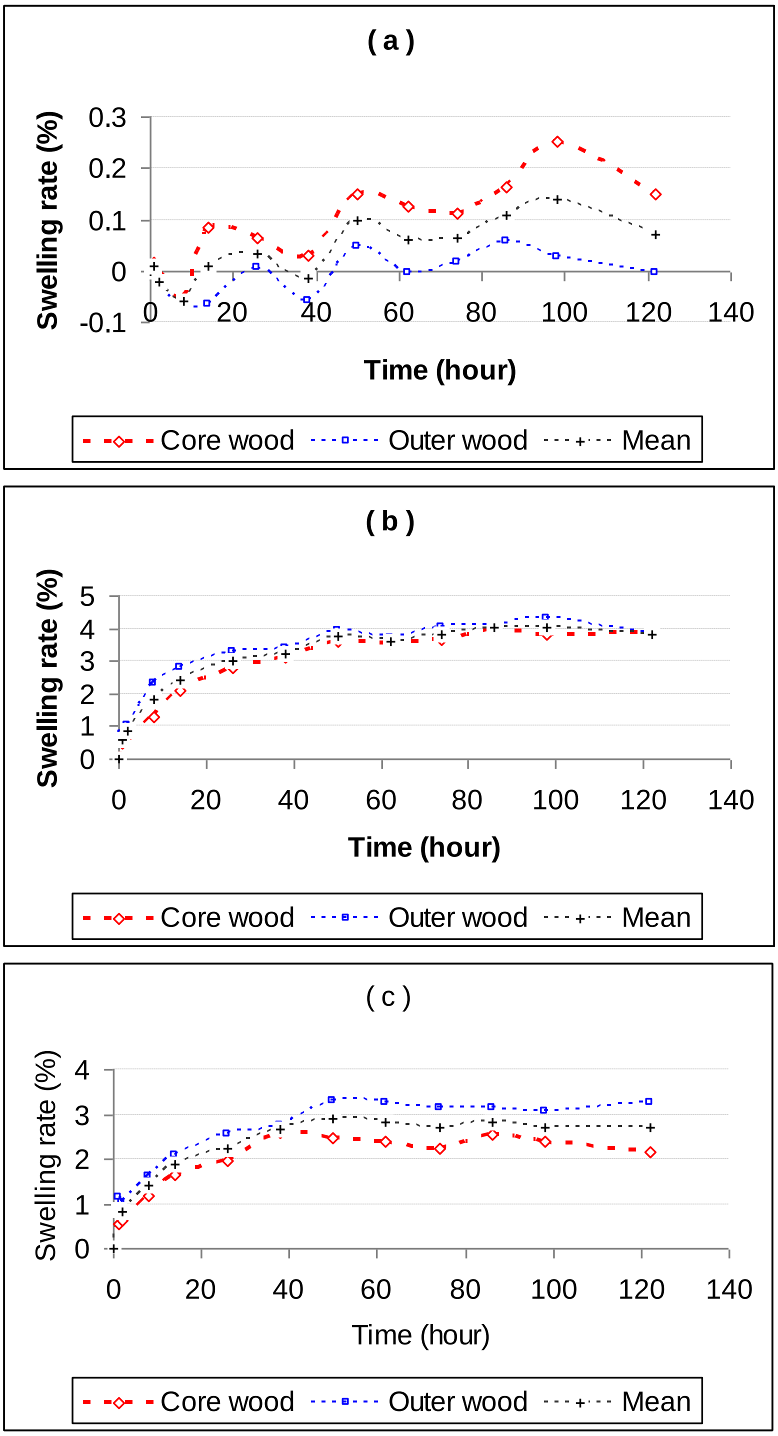


Figure 3-19: Comparison of wood swelling between core wood and outer wood, (a) longitudinal, (b) tangential and (c) radial directions

3.5 Conclusion

From the data obtained in this study, a number of useful points were found on New Zealand grown Douglas-fir's basic wood properties.

The basic wood density of Douglas-fir varies widely between trees. The mean value from 3 trees was measured to be 446.06 kg m^{-3}. The basic density varies in both radial and vertical directions. On cross section, the lowest value was found to be at location close to corewood boundary (about the 8^{th} growth ring). Samples from bottom disc tended to be denser than those from other height position.

At all stem heights, the highest longitudinal shrinkage value was found to be near to corewood boundary (about the 8^{th} growth ring). The variation of longitudinal shrinkage tended to be consistently stable between 0.1~0.2% in outerwood section (from the 15^{th} growth ring and outwards).

The bottom disc was found to have the highest longitudinal shrinkage, but the lowest tangential and radial shrinkage values. For tangential and radial shrinkage, the highest values were observed at 5.1m high and decreased upwards.

EMC results at different humidity obtained from this study were similar to the reported value. Bottom disc showed much lower EMC value than those from other stem heights. Douglas-fir sapwood (from 30^{th} growth ring and outwards) tended to have higher EMC values than its heartwood.

Chapter 4 Physical and Stability Properties of Radiata Pine

Douglas-fir is proving to be stiffer and stronger than radiata pine as a fact well known by builders. In order to make a systematic comparison between these two species, basic wood properties of radiata pine such as green moisture content, basic density, shrinkage and other moisture related properties were measured and presented in this chapter.

4.1 Green moisture content and basic density

4.1.1 Appearance of wood discs and green moisture content

From seven centre-pithed radiata pine trees, 23 wood discs were removed for the experiments (Note: Disc L2D2 was latterly discarded at sample preparation stage). Average diameter of each disc was measured and growth rings were counted before the preparation of test samples. The results of disc diameter as a function of stem height are shown in Figure 4-1 from which it can be seen that Tree L1 had the largest butt disc diameter of 432 mm. The corresponding growth ring number was 34. The butt disc diameters of other 6 trees ranged between 300 mm and 380 mm with average growth ring number of 27.

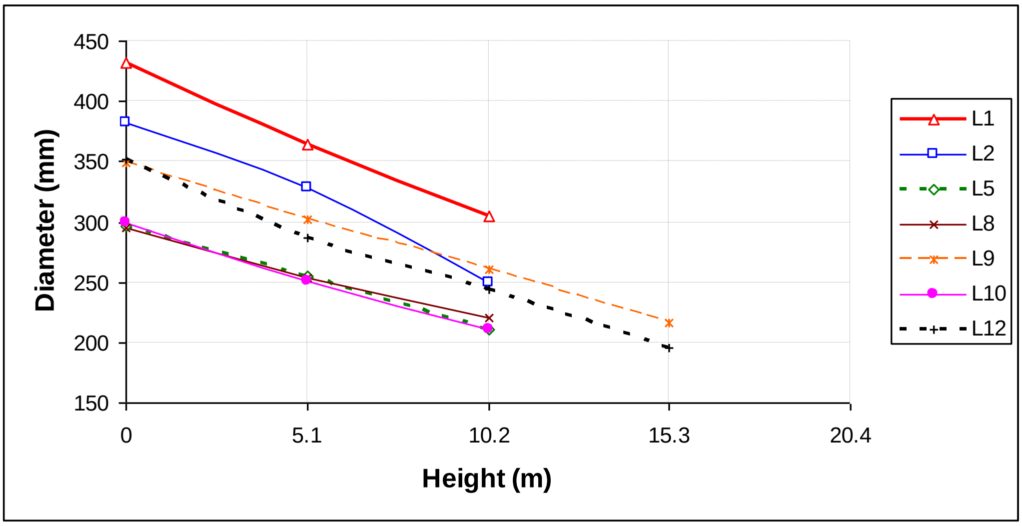


Figure 4-1: Diameter distribution of seven radiata pine trees as a function of tree height

Table 4-1: Summary of statistics for green moisture content (%) of radiata pine trees

	L1	L2	L5	L8	L9	L10	L12	All trees
Mean	122.40	158.62	110.80	112.87	110.53	108.73	114.07	118.12
Standard Deviation	50.45	42.27	60.20	42.97	52.95	47.94	57.21	53.02
Minimum	34.51	46.14	36.77	38.18	36.81	34.68	34.41	34.41
Maximum	189.22	205.39	194.08	176.81	191.22	193.69	201.75	205.39
No. of samples	58	30	38	38	56	36	55	311

From the 22 discs, 311 samples were prepared for measurement of green moisture content which ranged from 34.41% to 205.39% (Table 4-1). It was noted that a small amount of moisture was lost during preparation and handling, thus the measured data may be slightly lower than the true values. Since fibre saturation point of radiata pine is around 30% (Kininmonth, 1991), this loss of moisture would not affect shrinkage results. The overall mean green moisture content was 118.12% with standard deviation of 53.02%. The mean green moisture content of a tree varied between 108.73% and 158.62%.

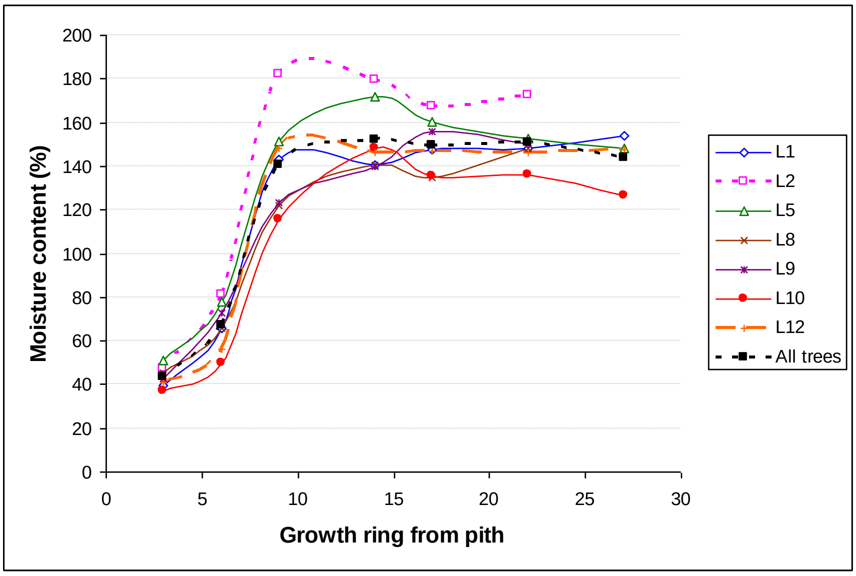


Figure 4-2: Variation of green moisture content of radiata pine along disc radius

Kininmonth (1991) reported that New Zealand radiata pine is characterised by a wide sapwood zone and high sapwood moisture content typically 120-180%. The radial variation of green moisture content for seven radiata pine trees was illustrated in Figure 4-2. The heartwood/sapwood boundary was considered at the 7th growth ring for 26-year-old radiata pine trees in this study, as the green moisture content value rose rapidly from around 60%% to an average value of 147.8% at this point. The average green moisture of heartwood was 55.3%, which was slightly higher than the value (45%) reported by Kininmonth (1991) and Walker (2006). The sapwood green moisture content value measured in this study is similar to the reported data by NZ Forest Research Institute (Walker, 2006).

4.1.2 Basic density

The wood basic density was measured using the same samples for green moisture contents, and the results are given in Table 4-2.

Table 4-2: Summary of statistics for basic density (kg m^{-3}) of radiata pine

	L1	L2	L5	L8	L9	L10	L12	All trees
Mean	391.82	373.41	354.37	376.86	371.79	410.57	410.53	385.51
Standard Deviation	46.52	27.20	29.27	38.41	36.62	56.58	54.16	47.15
Minimum	316.86	306.62	315.59	321.15	328.73	344.43	340.53	306.62
Maximum	573.14	422.64	436.35	514.48	539.75	638.64	593.31	638.64
Count	58	30	38	38	56	36	55	311

It can be seen in Table 4-2 that wood basic density of the 311 radiata pine samples ranged from 306.86 to 638.64 kg m^{-3} with an average value of 385.51 kg m^{-3} and standard deviation of 47.15 kg m^{-3}. A similar average value of 390 kg m^{-3} was reported for 25-year-old radiata pine tree by Walford (1985). In this study, the mean basic density of a tree ranged from 354.37 to 410.57 kg m^{-3}. According to the zoning system of Cown (1991), based on outerwood density, the forest site for extracting test samples in this study would fall into the low density zone, therefore, the average density measured in this study can be lower than the reported data from medium and high density zones in northern part of New Zealand.

Walker (2006) reported that corewood would be restricted to only 5 rings in low latitudes but would extend out to 15 rings in the south of New Zealand. In this study, corewood zoon was pronounced as the first 7 rings and outerwood was counted from the 16th ring outward. The average corewood density and outerwood density were 379.4 and 415.6 kg m^{-3}, respectively.

Figure 4-3 and Figure 4-4 show the variation of wood basic density of 7 radiata pine trees as a function of stem height (Figure 4-3) and growth ring number from pith to bark (Figure 4-4). From Figure 4-3, it is found that the average wood density decreased with increasing of the stem height. The difference in the average density between butt disc and 3rd disc (10.2 m) was 11.6%. Similar results have been reported by Cown (1991) in a survey of radiata pine wood properties.

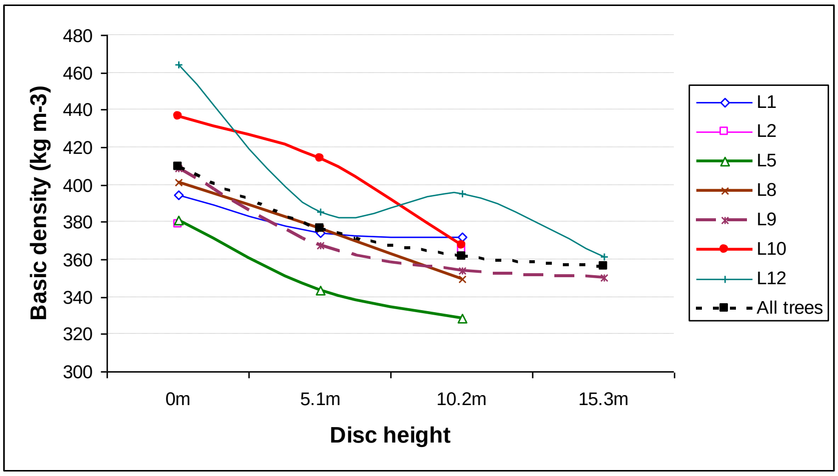


Figure 4-3: Vertical variation trend of basic density

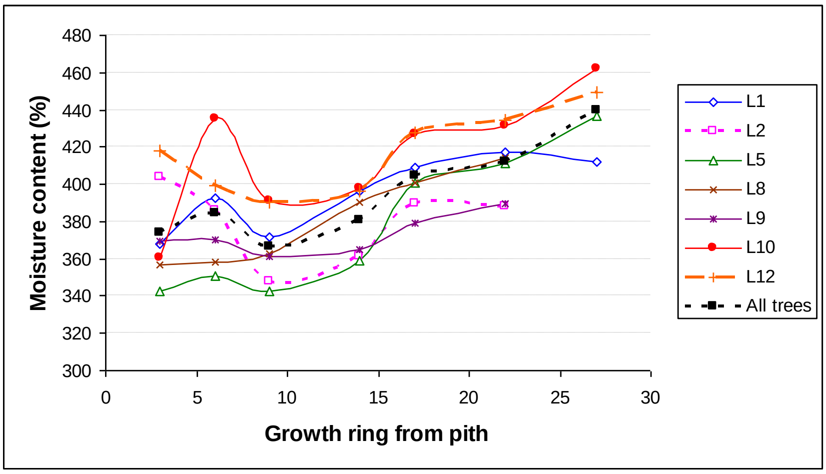


Figure 4-4: Radial variation of average wood basic density

An increasing trend of the wood basic density for radiata pine was expected from pith to bark at all height levels. However, a remarkable difference both in the values and the trend was observed in the corewood zone in all 7 trees (Figure 4-4). Tree L2, Tree L9 and Tree L12 showed decreasing tendency as the increase of growth ring numbers in their first 10 rings, while a peak value appeared in the same growth rings (around the 7th ring) for Tree L1, Tree L5 and Tree L10. Tree L8 presented fairly constant basic density in its corewood zoon. The above results may be slightly affected by the extractives and resin as in an ideal situation the data should be compared on an extractive free basis (Cown, 1991).

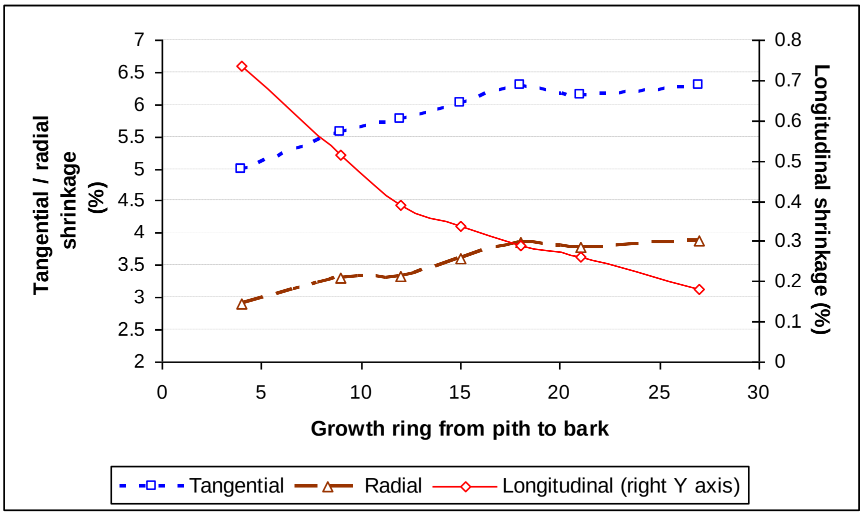
4.2 Shrinkage and swelling behavior

From 22 radiata pine wood discs, 310 samples were prepared for shrinkage and equilibrium moisture content (EMC) tests. Mean shrinkage values were determined at about 12% MC and oven-dry conditions in longitudinal, tangential and radial directions, respectively. Dimensional swelling rates were taken at 40%, 50%, 65% and 85% relative humidity (RH) conditions after oven-dry dimensions were measured.

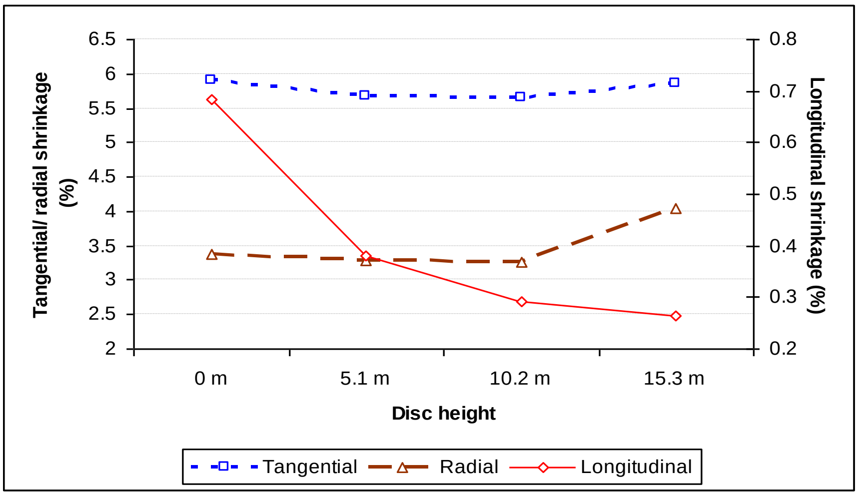
4.2.1 Shrinkage variations

The results of measured shrinkage at oven dry are shown in Figure 4-5 (a) as a function of growth ring number counted from the pith and in Figure 4-5 (b) as a function of stem height. From Figure 4-5 (a), it is seen that at all stem heights, the values of average tangential shrinkage and average radial shrinkage increased progressively with the increasing of growth ring number from pith to bark, while the average longitudinal shrinkage showed decreasing trend from the pith to bark. The average longitudinal shrinkage in the first 5 growth rings was 0.73% as shown in Figure 4-5 (a) (right Y axis), while the value close to bark was only 0.18%.

From Figure 4-5(b), it can be seen that the longitudinal shrinkage value decreased significantly with the increasing height in the tree, although the variation of tangential shrinkage and radial shrinkage was not clearly pronounced. Between the height of 0m and 10.2m, the value of tangential shrinkage and radial shrinkage tended to decrease, but from the height of 10.2m and above, the values rose again and reached their highest score at 15.3m high position.



(a)



(b)

Figure 4-5: Variation of anisotropic shrinkage of radiata pine at oven dry as a function of growth ring number (a) and as a function of stem height (b)

Cown and McConchie (1991) found there was a very slight decrease in tangential and radial shrinkage values with increasing heights in the tree at a similar radial position. The variation of shrinkage with stem height is shown in Figure 4-5(b). The change in tangential and radial shrinkage along the stem height is not obvious which is consistent with previous findings by Cown et al. (1991). However, the longitudinal shrinkage of radiata pine tended to decrease with increasing of the stem height with its value changing from 0.68% at ground location to 0.26% on the top of tree. Therefore, butt disc tended to shrink much more than the discs from other stem heights in longitudinal direction.

The summary of shrinkage of radiata pine at 12%MC and oven dry conditions is shown in Table 4-3. The overall average shrinkages in the longitudinal, tangential and radial directions from green to 12% moisture content were 0.26%, 2.94% and 1.37%, respectively whereas the corresponding values from green to oven dry were 0.54%, 5.62% and 3.21%. The mean volumetric shrinkage of radiata pine samples at oven-dry was 9.30%.

Table 4-3: Directional shrinkage values for radiata pine

	Green MC	Shrinkage from green to oven dry (%)				Shrinkage from green to 12% moisture content (%)		
	(%)	*L*	*T*	*R*	*Vol*	L	T	R
Mean	119.50	0.54	5.62	3.21	9.30	0.26	2.94	1.37
Standard Deviation	53.88	0.45	0.87	2.57	2.66	0.25	0.86	1.04
Minimum	33.44	0.02	3.34	1.05	5.62	0.00	0.41	0.00
Maximum	210.35	2.34	7.87	6.60	14.12	1.11	6.50	6.34

Shrinkage measured by Cown and McConchie (1980) on material from ten 52-year-old radiata pine trees showed greater value both in tangential direction (7.0% for oven-dry and 4.2% for 12% MC) and in radial direction (3.4% for oven-dry and 2.0% for 12% MC), while the longitudinal shrinkage values (0.25% for oven-dry and 0.02% for 12%MC) by Cown and McConchie (1980) were much smaller than those from this study. According to NZFRI data reported in 1992, the longitudinal shrinkage from green to 12% moisture content was 0.1% and at oven-dry condition was 0.2%. Lower tangential and radial shrinkage value in this study is possibly due to tree age effects, however, radiata pine samples in this study tended to exhibit high longitudinal shrinkage values (mean of 0.54% and up to 2.34%).

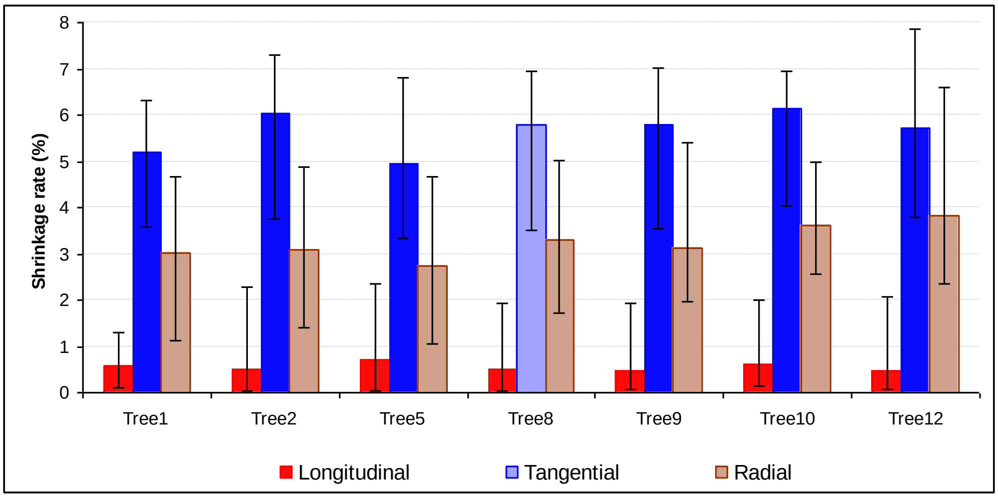


Figure 4-6: Variation of shrinkage between 7 radiata pine trees

Figure 4-6 illustrates the overall values of the longitudinal, tangential and radial shrinkage in seven radiata pine trees averaged over 3 stem heights (0m, 5.1m and 10.2m). The error bars show the data variability at 95% confidence level. Significant differences between trees were found in this study, however, no clear correlation was observed between shrinkage and disc diameter.

4.2.2 Longitudinal shrinkage

The variation pattern found in this study is consistent with the earlier reported data (Cown,1991; Herritsch, 2007; Pang 2001). However, it was found that the earlier reported longitudinal shrinkage was much lower than the values from the current study as shown in Table 4-4.

Table 4-4: Comparison of longitudinal shrinkage from green to oven-dry between this study and literature data

Source	Cown and McConchie (1983)	Pang (2001)	Herritsch (2007)	This study
Value	0.25	0.38	0.39 ±0.26	0.54 ±0.45

Figure 4-7 shows the longitudinal shrinkage at different stem heights as a function of growth ring number. It is widely accepted that pith-to-bark variation in longitudinal shrinkage is a key factor for warp in timber drying. However, Kilger (2003) reported that the difference in the longitudinal shrinkage between two faces of board explained spring or bow much better when the variation in shrinkage along the timber was considered. Herritsch (2007) reported that the longitudinal shrinkage of radiata pine tended to increase with the height, which is opposite to the trend found in this study.

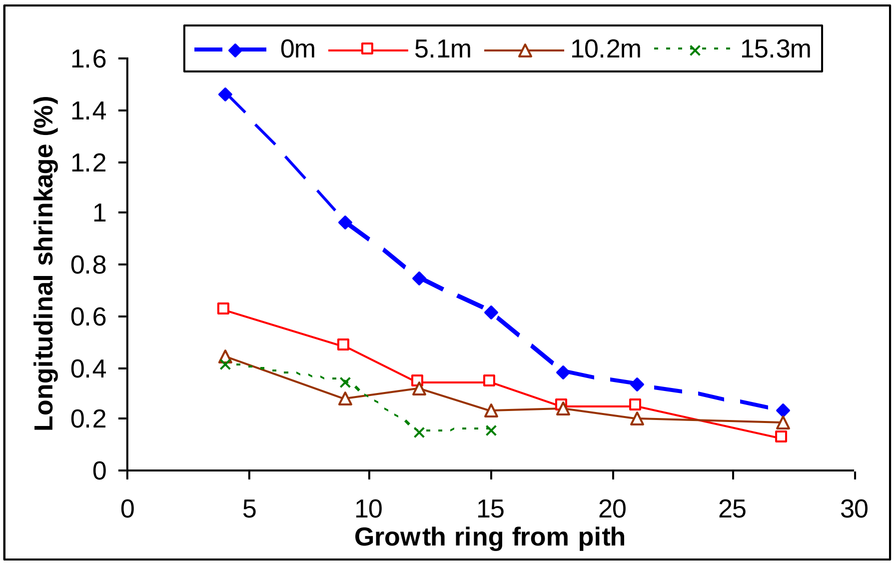


Figure 4-7: Variation of oven-dried longitudinal shrinkage rate of radiata pine

Microfibril angle (MFA) was believed to be the main cause of high variation in longitudinal shrinkage. Meylan (1968) examined the longitudinal and tangential shrinkage in the corewood of *Pinus jeffreyi* where the microfibril angle could exceed 40 °and the longitudinal shrinkage was as high as 7% which was well in excess of the tangential shrinkage in 'normal' samples. It was reported for 22-year-old trees of *Pinus radiata* by Donaldson (1992) that mean microfibril angles varied from 9 °to 55 ° with the highest MFA occurring in the corewood of the butt log, and angles also showed a curvilinear decline from pith to bark, which was more pronounced at the butt end of the stem. Herritsch (2007) reported that the tangential shrinkage decreased with the tree height, which followed the same trend as the MFA. However, many other factors including density (Pilura *et al.*, 2005), spiral grain, and latewood proportion (Walker, 2006) will also affect the shrinkage variation of wood, although MFA was believed to be the main cause of the high longitudinal shrinkage in corewood. Therefore, variation in MFA (Donaldson, 1992) together with density (Cown, 1992) of radiata pine can be able to explain the variation of anisotropic shrinkage to a certain level. The longitudinal shrinkage variations along the cross section radius for radiata pine were mainly caused by corewood, which has great spiral grain angle (Cown *et al.*, 1991) and MFA (Donaldson, 1992).

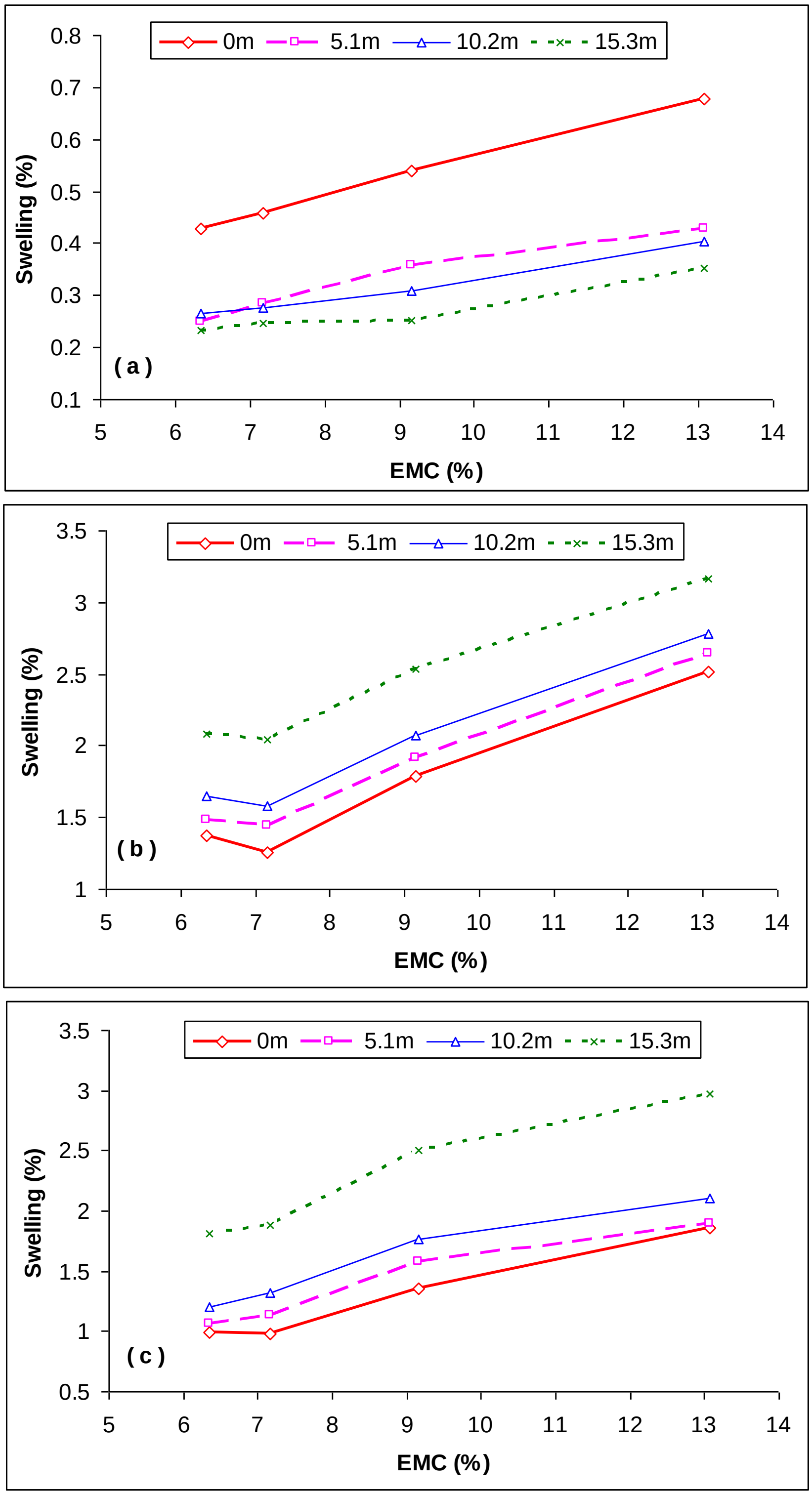


Figure 4-8: Variation of dimensional swelling for radiata pine: (a) longitudinal, (b) tangential, and (c) radial

4.2.3 Directional swelling in the environment chamber

After the shrinkage measurement, all the shrinkage samples were oven dried and then placed in an environment chamber at 30^{o}C, the change of dimension and weight for samples was measured in adsorption process at 40%RH, 50%RH, 65%RH and 85%RH, respectively. Figure 4-8 shows the variation of average dimensional swelling in longitudinal, tangential and radial directions. It can bee seen that the swelling of radiata pine was the greatest in tangential direction, and minimum in longitudinal direction. The variations of swelling for radiata pine are similar to those measured for Douglas-fir samples which were placed in the same environment chamber. The overall average directional swelling was lower than the corresponding shrinkage with the same moisture content change below the fibre saturation point.

The tangential and radial swelling tended to increase with the increasing of stem height, while the swelling in the longitudinal direction decreased as stem height increased. The butt discs (0m) had the greatest longitudinal swelling and the top discs (15.3m) had highest tangential and radial swelling compare to the discs from other stem positions.

4.3 Equilibrium moisture content and fibre saturation point

4.3.1 Equilibrium moisture content

In order to compare water related wood basic properties with Douglas-fir, equilibrium moisture content (EMC) of radiata pine samples was calculated at four different relative humidity (RH) conditions (40%RH, 50%RH, 65%RH and 85%RH) at 30^{o}C during desorption and adsorption process. Moisture sorption isotherms at 30^{o}C was determined and typical curves for desorption/adsorption are shown in Figure 4-9.

From the experimental results, the following behaviour has been confirmed. Firstly, the MEC increased with RH at a given temperature, as expected. In this study, the EMC values of radiata pine samples at 30 ^{o}C were 8.5%, 9.6%, 12.1% and 16.2% at relative humidity of 40%, 50%, 65% and 85%, respectively. Secondly, the EMC value during desorption was higher than for adsorption with about 2 ~ 3% MC apart which is called hysteresis. For example, at 65% RH, the moisture content going from wet to dry is 12.1%, whereas the same wood samples going from dry to wet would have a moisture content of 9.2%. This difference tended to increase as the RH increased at a given temperature.

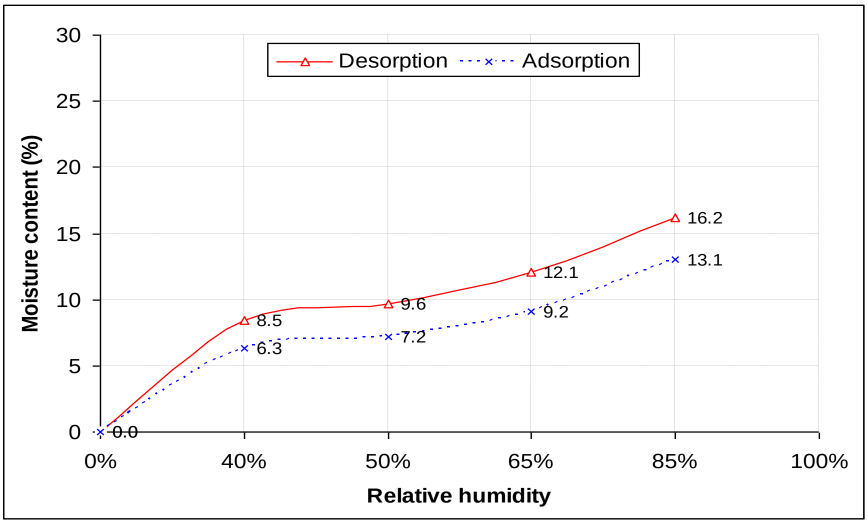


Figure 4-9: Moisture sorption isotherm of radiata pine, at 30 °C

The equilibrium moisture content is also affected by the temperature with the EMC decreasing with increase of the temperature. Differences exist between different species, but they are exhibited mainly at high relative humidity (Tsoumis, 1991). Herritsch (2007) reported EMC values of New Zealand radiata pine at 40%RH, 60%RH and 85%RH at 30°C were 9.05%, 12.31% and 21.27%, respectively. These values were considerable higher than the values observed from this study. However, the data received from this study were close to the other published values (Kininmonth, 1991; Tsoumis, 1991).

The EMC results from this study are illustrated in Figure 4-10 for variation along the stem height and in Figure 4-11 for variation along the disc radius (growth ring number). From Figure 4-10, no remarkable difference was found between different stem heights. Similarly, insignificant difference was found along the disc radius, meaning the difference between radiata heartwood and sapwood was not significant. These results are consistent with those reported by Harris (1961).

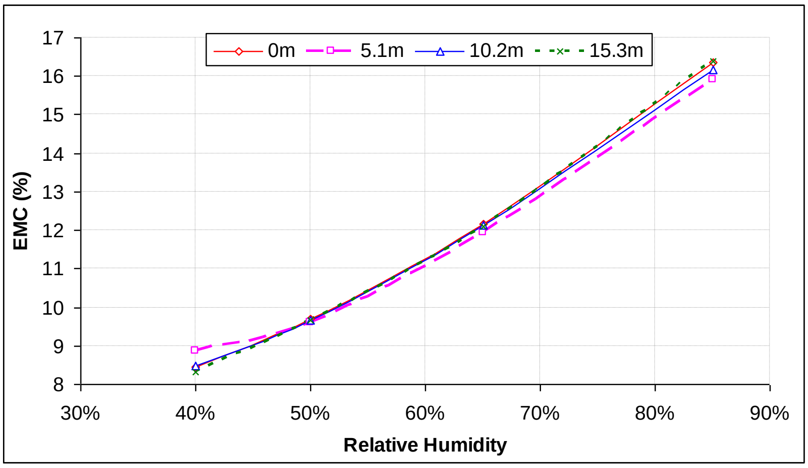


Figure 4-10: Variation of average EMC along the stem height

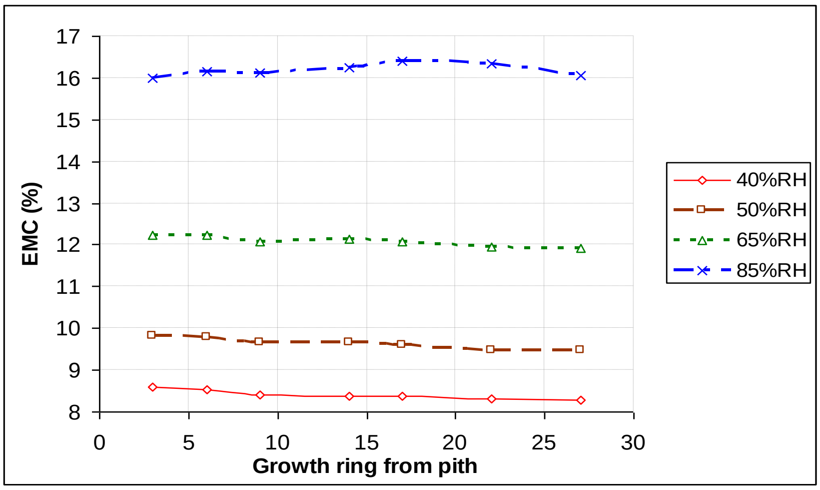


Figure 4-11: Variation of average EMC along the disc radius

4.3.2 Fibre saturation point

Fibre Saturation point (FSP) is the moisture content at which the cell cavities contained no liquid water, but the cell walls were fully saturated with bond water. The differences of FSP may be observed in the same species, depending on method of determination and other factors, such as extractive content, earlywood and latewood, compression and tension wood, density and temperature. The FSP decreases with increasing of temperature at a rate of 0.1% moisture content per degree increase in the temperature (Tsoumis, 1991).

As the wood starts to shrink once the moisture content is reduced below the FSP, the FSP of radiata pine can be determined using the tangential shrinkage-moisture content relationship and using the correlation between the volumetric shrinkage and wood basic density. In Figure 14-12, the FSP of radiata pine was determined from the correlation plot of tangential shrinkage against moisture content. FSP is the MC value at the intersection point of shrinkage line with the vertical axis. The average FSP of 25.61% MC for radiata pine samples at 30°C was determined from above negative linear equitation in this study. This value was lower than the reported value of 29% at room temperature in Timber Design Guide (Miller, 1999). Figure 4-13 is a plot of volumetric shrinkage of radiata pine samples. In this method the moisture content at FSP (slope coefficient of regression line) is 24.3%. This value will be used to compare water related properties with New Zealand grow Douglas-fir in Chapter 7.

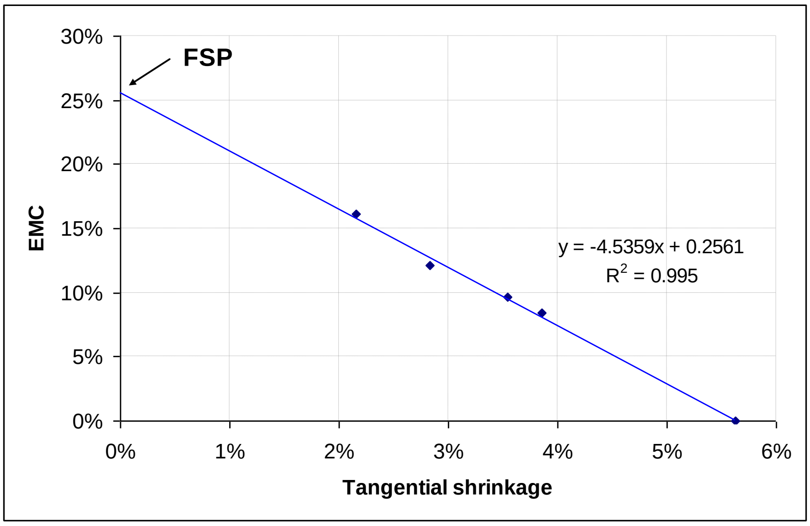


Figure 4-12: Determination of FSP from the linear relationship of tangential shrinkage and moisture content

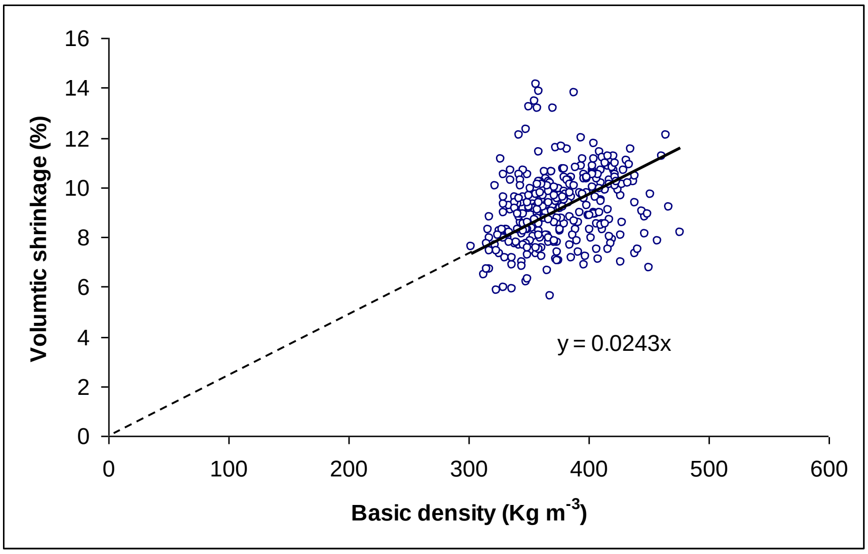


Figure 4-13: Volumetric shrinkage from green to oven-dried against basic density

4.4 Water resistant properties

4.4.1 Water absorption property and water swelling variation

In water resistant property experiment, water absorption and dimensional swelling of radiata pine samples were tested in a water bath which temperature was controlled at 20°C. The effects of corewood and outerwood were discussed in this section. Figure 4-14 shows the variation of water absorption through three direction (longitudinal, tangential and radial) over 2000 hours of immersion. In the figure, the horizontal axis represents the total immersing time in water bath, and the vertical axis illustrates the total amount of water (g) absorbed by the wood samples through per unit area (cm^2) of the exposed surfaces.

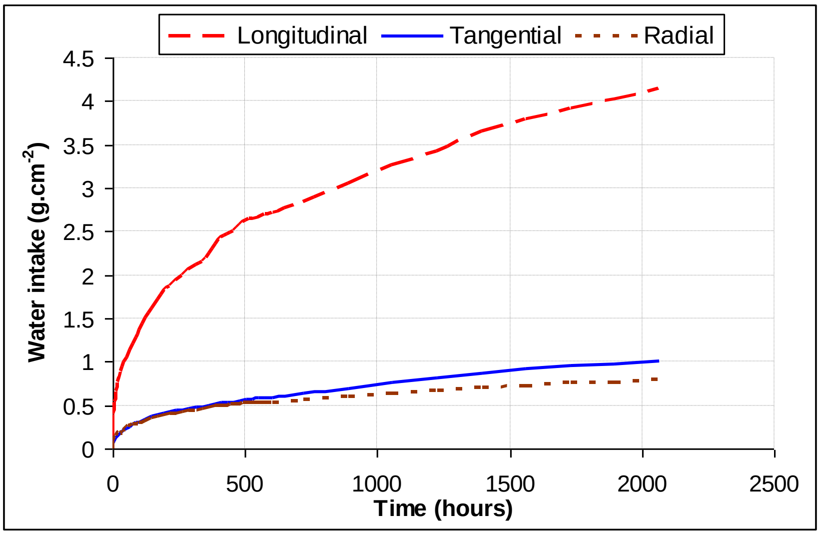


Figure 4-14: Water absorption of radiata pine under water bath at 20°C

Water was rapidly absorbed into radiata pine wood samples under water bath condition in the initial immersion. The absorption was the greatest in the first 2 hours, then gradually slowed down and reached maximal value. In the same manner as Douglas-fir, the water absorption capability of radiata pine was the highest in longitudinal direction. During the same period of time, the total amount of water soaked from longitudinal surfaces was about 4 times higher than from other surfaces.

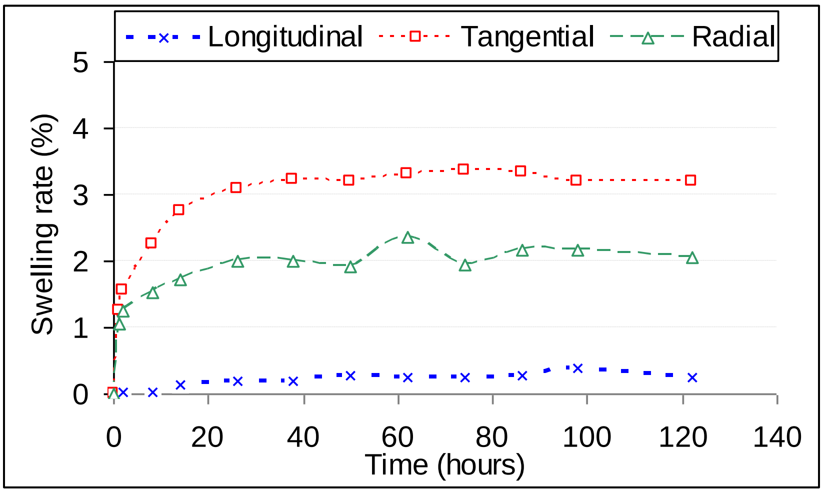


Figure 4-15: Swelling of radiata pine samples under water bath at 20°C

The water swelling of radiata pine wood at 20°C is shown in Figure 4-15. Since the water swelling is based on the ratio of dimensional changes divided by the original dimension, the effect of sample dimension can be eliminated. Similar to water absorption property, anisotropic water swelling was the fastest in the first 2 hours and then gradually achieved its maximum value after about 24 hours. The equilibrium swelling of radiata pine was 0.27%, 3.2% and 1.9% in longitudinal, tangential and radial directions, respectively.

4.4.2 Comparison of radiata pine corewood and outerwood

As mentioned in Chapter 1, corewood is identified to have undesirable wood properties including lower strength, lower stiffness and high longitudinal shrinkage. From this study, the water absorption is also investigated on the effect of corewood and outwood. Figure 4-16 shows the water absorption in corewood and outwood of radiata pine sample in longitudinal, tangential and radial directions.

Similar to Douglas-fir samples, radiata pine outerwood showed significant higher water absorption in longitudinal direction than the corewood. Under water bath condition, the mean MC of the outerwood samples was found to be 20% higher than the corewood samples as shown in Figure 4-16 (a). This difference was not obvious observed in tangential (b) and radial (c) directions. In contrast, the average MC of radial-surface-exposed corewood samples tended to be higher than the outerwood samples after 1000 hours immersion in water bath as shown in Figure 4-16 (c).

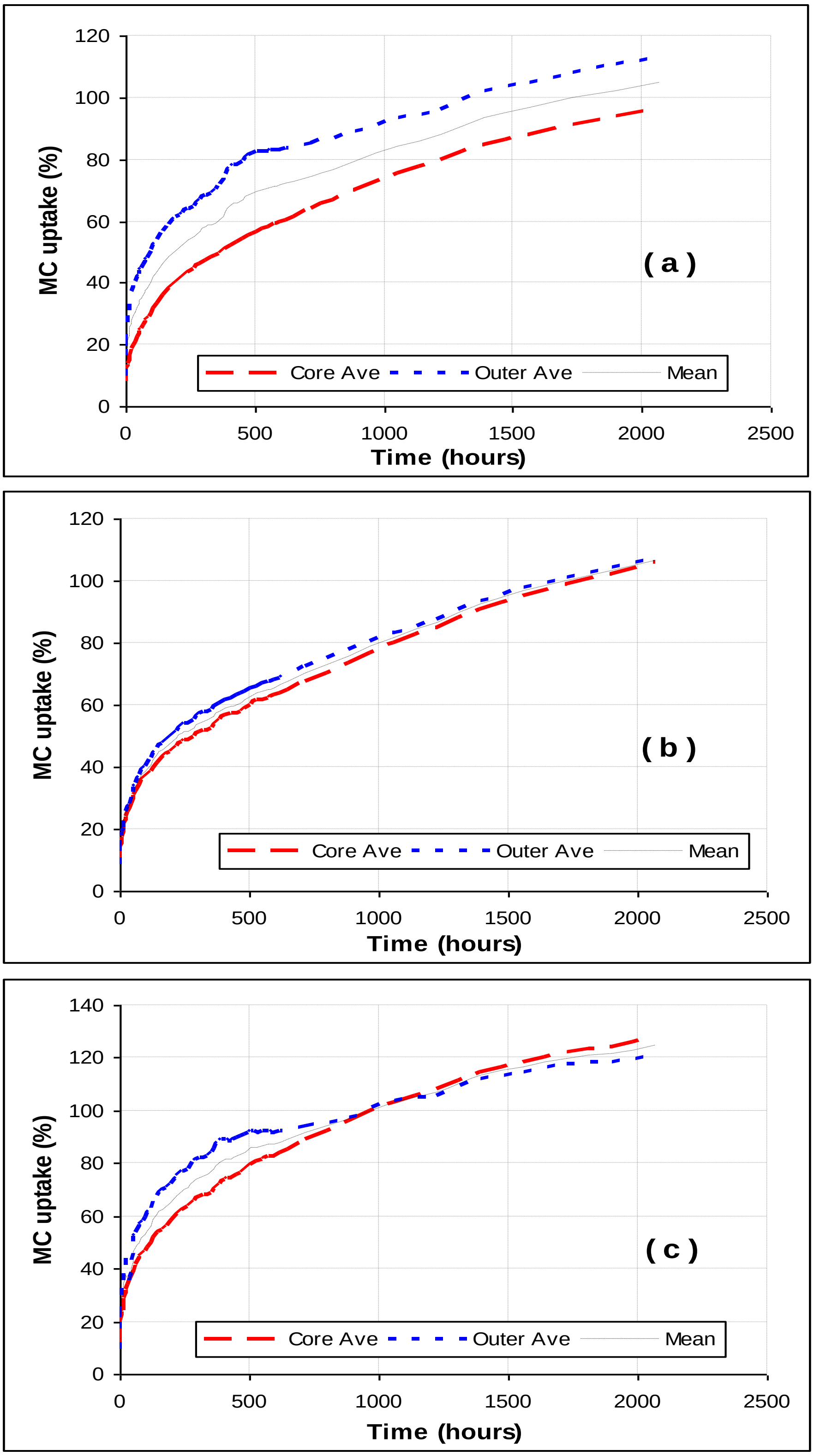


Figure 4-16: Comparison of water absorption between corewood and outerwood: (a) longitudinal, (b) tangential, and (c) radial

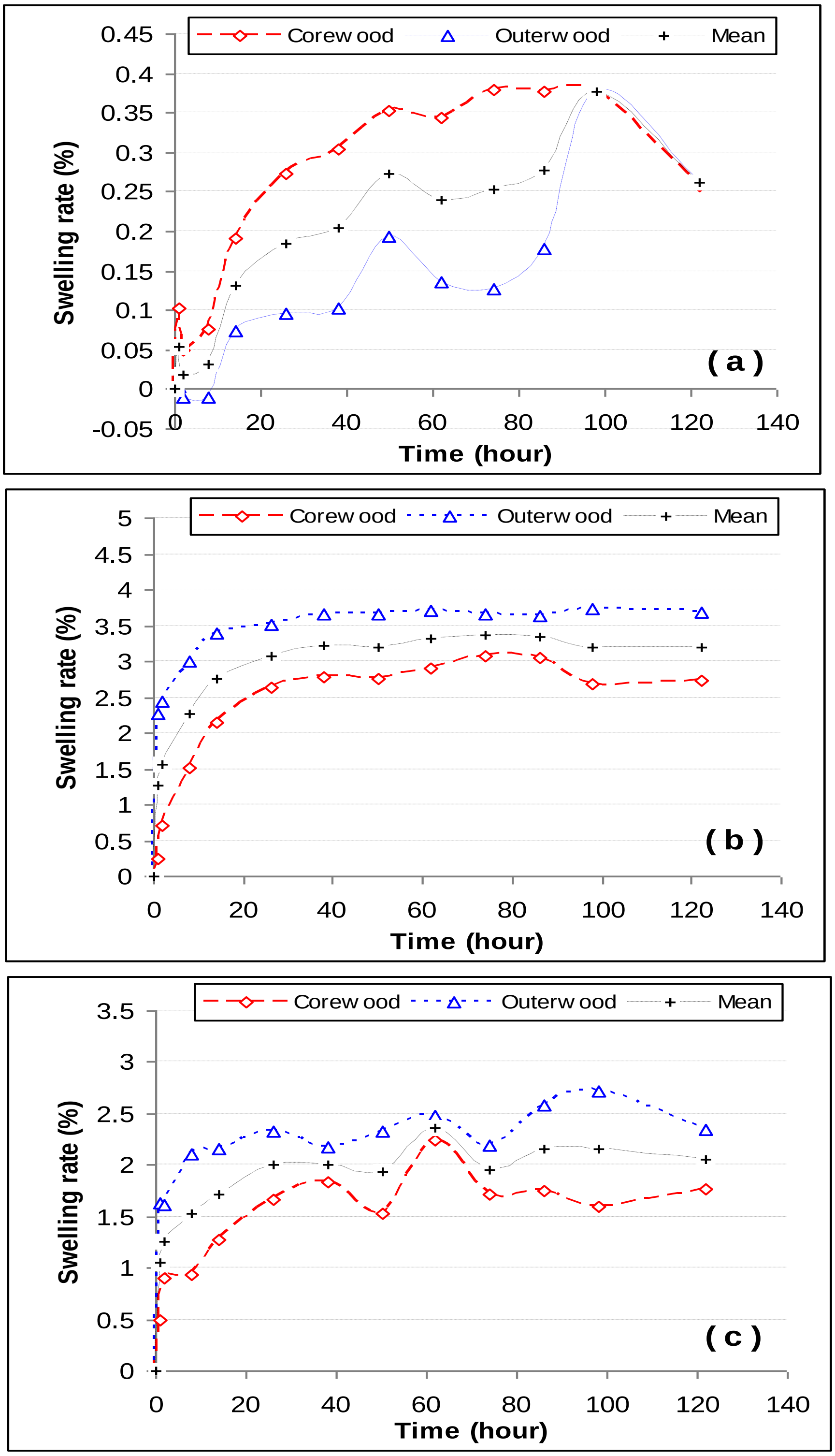


Figure 4-17: Comparison of swelling rate between corewood and outerwood: (a) longitudinal, (b) tangential, and (c) radial

Figure 4-17 shows the comparison of water swelling (%) between corewood samples and outerwood samples in longitudinal, tangential and radial directions. The radiata pine outerwood tended to swell more in tangential and radial directions, and less in longitudinal swelling than the core wood. The longitudinal swelling of radiata pine corewood was higher than outerwood in the first 80 hours of water immersion with an average difference of 0.2%. In tangential and radial directions, this difference was about 1%.

It was shown in Figure 4-17 (b) and (c) that it took less than 24 hours for radiata pine samples to reach maxima swollen dimensions in tangential and radial directions. Longitudinal swelling (Figure 17a) shows continuous increasing trend over a period of 50 hours when the tangential and the radial swelling had reached the equilibrium values.

Chapter 5 . Distortion and Mechanical Properties of Douglas-fir

Timber distortion, i.e. spring, bow and twist, has been acknowledged as an important factor of sawn timber quality, especially for structural timbers. In this chapter, the dimensional stability of New Zealand grown Douglas fir timber is reported. The results are discussed with comparison of the experimental data obtained from small clear wood sample studies reported in Chapter 3. Timber distortion properties and its variation were considered within and between trees. In addition, acoustic velocity measurements were used to describe mechanical properties and the relationships between timber distortion and stiffness are also reported.

5.1 Dimensional stability of Douglas-fir timber

In this study, 210 Douglas-fir boards with dimensions of 100mm×50mm ×4.8 m were produced from 9 trees. All of these boards were visually graded (VGD) as VGD-1, VGD-2 and VGD-B following AU/NZ visual grading standard and the results are given in Table 5-1. From the results, totally 173 Douglas-fir timber (86.6%) were visual graded as VGD-1 class, 23 pieces were felling into VGD-2, and 4 boards (about 2%) were visually rejected from structural timber.

Table 5-1: Visual grading of Douglas fir samples

Visual grade	No. of samples	Frequency (%)
VGD-1	173	86.5
VGD-2	23	11.5
VGD-B	4	2

After the visual grading, weight of each board was measured and then after timber drying. Moisture content was measured by electrical moisture meter reading. The deviation (3%) of the meter reading to actual MC value of Douglas fir sample was calibrated through oven dry method. After the MC value was determined, the oven-dry weight of each Douglas-fir board was estimated based on the weights measured:

$$MC(\%) = \frac{\text{mass of wet wood} - \text{mass of oven dry wood}}{\text{mass of oven dry wood}} \times 100\% \qquad \textbf{(1)}$$

Table 5-2: Shrinkage distribution of Douglas-fir full-sized timber

Group	Flat-sawn timber			Quarter-sawn timber		
	MC (%)	TS (%)*	RS (%)**	MC (%)	TS (%)*	RS (%)**
C90	14.4(0.89)	1.58(0.59)	1.60(0.58)	16.0(1.21)	1.78(0.73)	1.80(1.09)
C70	15.1(0.97)	1.85(0.35)	1.80(0.30)	15.1(1.35)	1.31(0.26)	1.10(0.20)
C30	15.0(1.32)	1.82(0.35)	1.70(0.35)	16.1(0.36)	1.44(0.41)	1.21(0.26)
C10	16.2(1.31)	1.95(0.24)	1.71(0.27)	15.6(0.07)	1.78(0.32)	1.51(0.35)
Overall:	15.2(1.27)	1.81(0.40)	1.70(0.38)	15.6(1.12)	1.45(0.44)	1.27(0.53)

**TS: Tangential shrinkage* ***RS: Radial shrinkage*

Note: Numbers in brackets are standard deviation.

By measuring the board dimensions both before and after kiln drying, the shrinkage in board width and thickness of full-sized Douglas fir boards were determined and the results are given in Table 5-2. The boards were classified into 4 groups according to corewood proportion and divided into flat-sawn and quarter-sawn timbers based on the ring orientation over the end sections. Depending on the sawing pattern of boards, the width and thickness shrinkage in the flat sawn boards corresponded to shrinkage in tangential and radial directions whereas in quartersawn boards, the width and thickness shrinkage was consistent with radial and tangential shrinkage.

.The overall shrinkage values in tangential and radial directions were both 1.6% at an average MC of 15.3%. These values were much less than the experimental values obtained from small clear wood sample presented in Chapter 3 (2.97% for tangential and 1.78% for radial at 12% MC). However the same variation trend (pith to bark) was found in flat-sawn timbers that the shrinkage values increased when the corewood proportion decreases. No clear trend was found with the quarter-sawn timbers possible due to the large number of growth rings contained in the quarter sawn timber thus the variation in the radius direction was smoothed out.

5.2 Shape stability of Douglas-fir full-sized timber

5.2.1 Drying distortion results and classification of Douglas-fir samples

After drying, all timbers were graded according to distortion tolerances as shown in Table 5-3, which was designed based on New Zealand Timber Grading Rules (*NZS 3631*: 1988) and others relative researches (Haslett, 1991; Cai et al., 2007; Perstorper et al., 2001; Tarvainen, 2005). Timbers of Grade A have excellent shape stability while those of Grade D show the excessive distortion and should be rejected according to NZ standard. Grade B and Grade C timbers show distortion classes between Grade A and D , which are still acceptable for structural uses.

Table 5-3: Distortion tolerances (mm/50mm/100mm/4.8m) and grading

Grade	A	B	C	D
Spring	≤5	5～15	15～30	>30
Bow	≤10	10～30	30～60	>60
Twist	0	≤5	5～10	>10

** Maximum warp permissible in 4.8-m length of 100×50-mm timber (NZS 3631:1988) is twist 10mm, spring 30 mm, bow 60 mm.*

For each board, the individual type of distortions was classified into Grade A, B, C and D through measurements as shown above. The final grade of board was dependent on the lowest grade in the three types of distortion. For example, timber No.5036 was classified to Grade C in spring, Grade B in bow and Grade D in twist after distortion measurement. The final grade is Grade D timber ofr its lowest grade in twist. In this way, once a piece of board is found to have extreme distortion beyond permitted values in any individual type of distortion, it would be defined as Grade D timber and rejected from structure timbers.

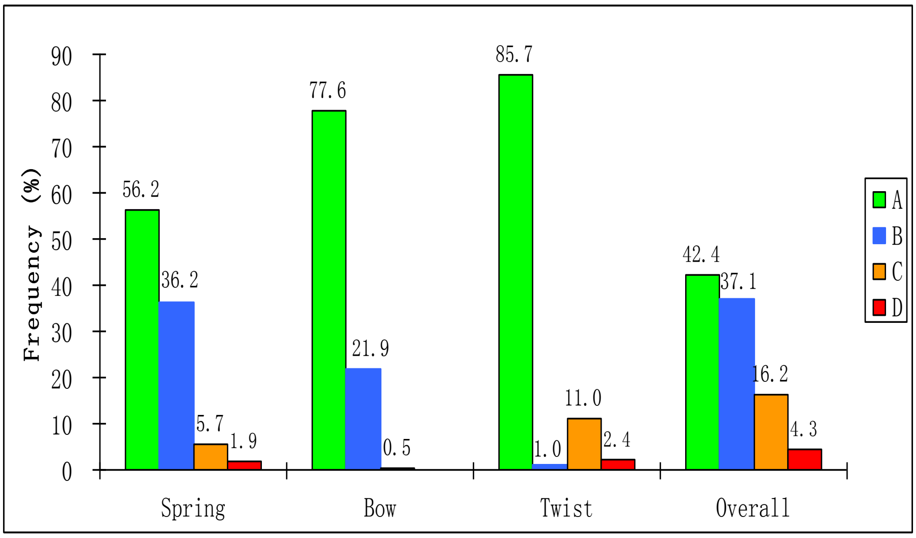


Figure 5-1: Distribution of drying distortion of Douglas fir timbers

Figure 5-1 illustrates the distribution of timber distortion of Douglas-fir for spring, bow and twist. The results show excellent timber shape stabilities performance of Douglas-fir with more than 95% of the boards being graded as accepted classes, Grade A, Grade B and Grade C. Only 4.3% of the timbers were tested to have excessive distortion according to New Zealand Grading rules. This advanced stability performance could be mainly attributed to its comparatively small longitudinal shrinkage value (0.12% at 12%MC, see Table 3-3).

When only twist was considered, 97.6% of all studs fulfilled the requirement of maximum 10 mm twist. According to Figure 5-1, 98.1% of the boards fulfilled the requirement of maximum 30 mm spring. The distortion of bow is not an issue for Douglas fir, as almost 100% of experimental samples showed great performance (Grade A and B) in bow. Twist is generally related to a combination of large spiral grain and the anisotropic shrinkage in a piece of timber as stated in Chapter 1. Bow and spring are usually related to presence of corewood and other growth characteristics.

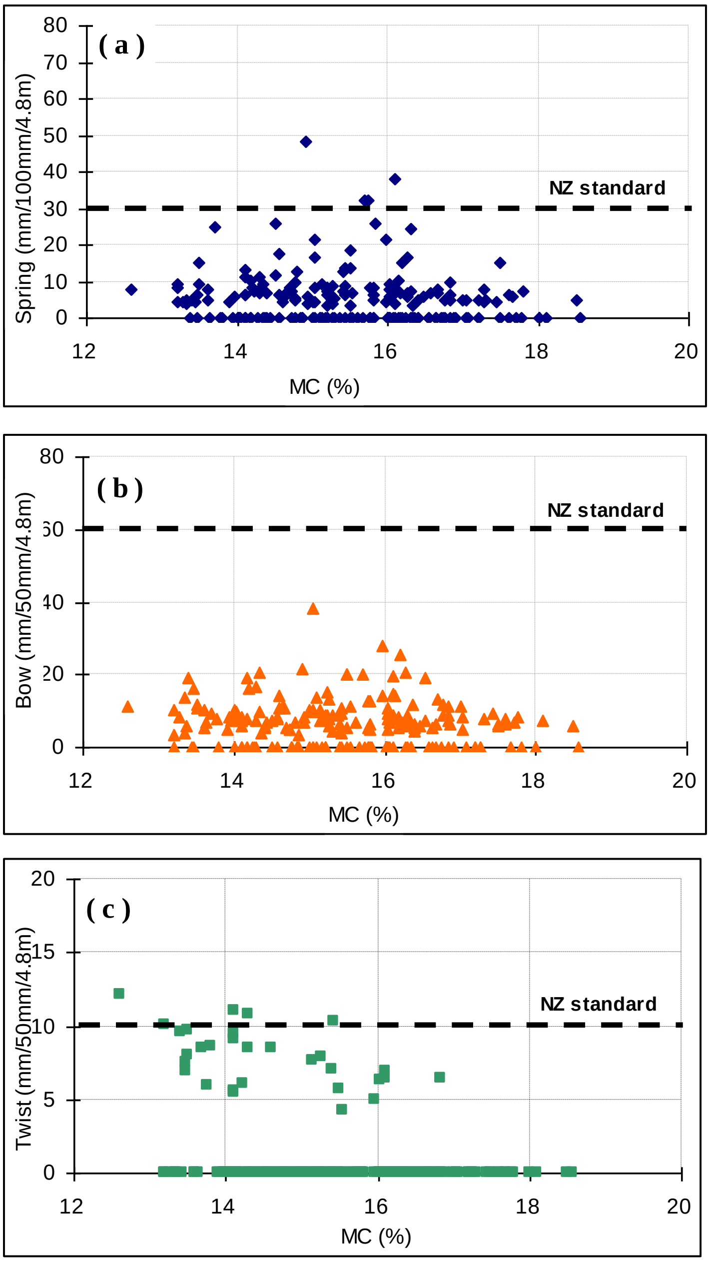


Figure 5-2: Drying distortion of Douglas-fir timber as a function of final MC: (a) spring, (b) bow, and (c) twist

5.2.2 Factors affecting the drying distortion of Douglas-fir timbers

In Figure 5-2, all of the timber distortion data are presented as a function of moisture content for spring (Figure 5-2a), bow (Figure 5-1b) and twist (Figure 5-2c). From the figure, it can be seen that twist and spring are the main reason to cause timber rejection under New Zealand standard, but spring and bow are the most visible deformation expressions for Douglas-fir timber. Totally 9 boards were graded as Grade D for rejection, 5 of which was from extreme twist and 4 from spring.

In the timber drying, all boards were firstly dried to an average MC of 18.4%, then were equalised for two more days to an average MC of 15.4%. The final MC of the boards ranged between 12 % and 19%, however no significant correlation was found between final MC and drying distortions. At the average final MC of 15.4%, mean distortions of the 100mm (width) $\times$ 50mm (thickness) $\times$ 4.8 m (length) Douglas fir timber were 5.4 mm, 6.4 mm and 1.1 mm on spring, bow and twist, respectively.

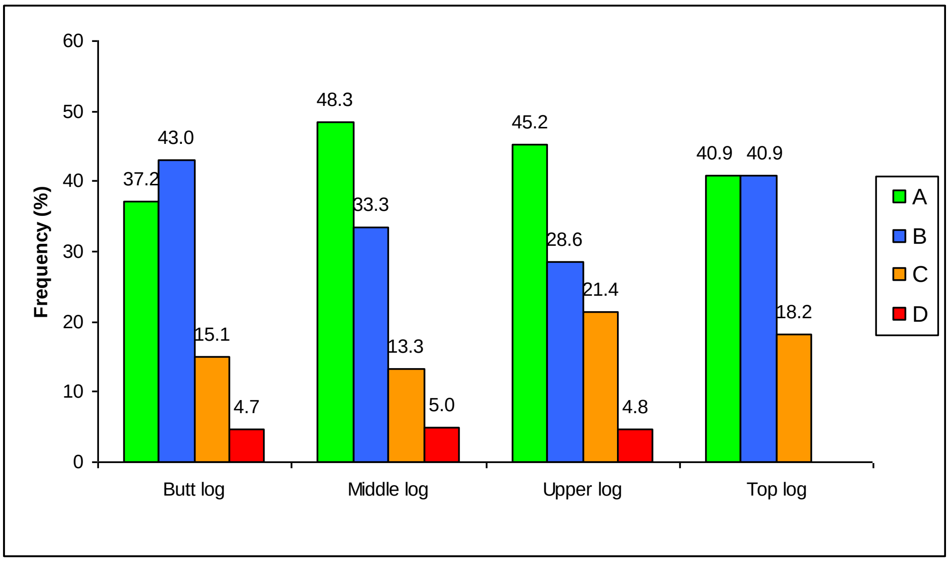


Figure 5-3: Effects of stem height on the timber distortion

Figure 5-3 illustrates the distribution of timber distortion of Douglas-fir as a function of stem height where the boards were originated. It was shown that the down-graded timbers did not seem to be affected by the longitudinal position in the tree, although more boards from high position logs fell in better stability grades (Grade A and Grade B) than those from butt logs.

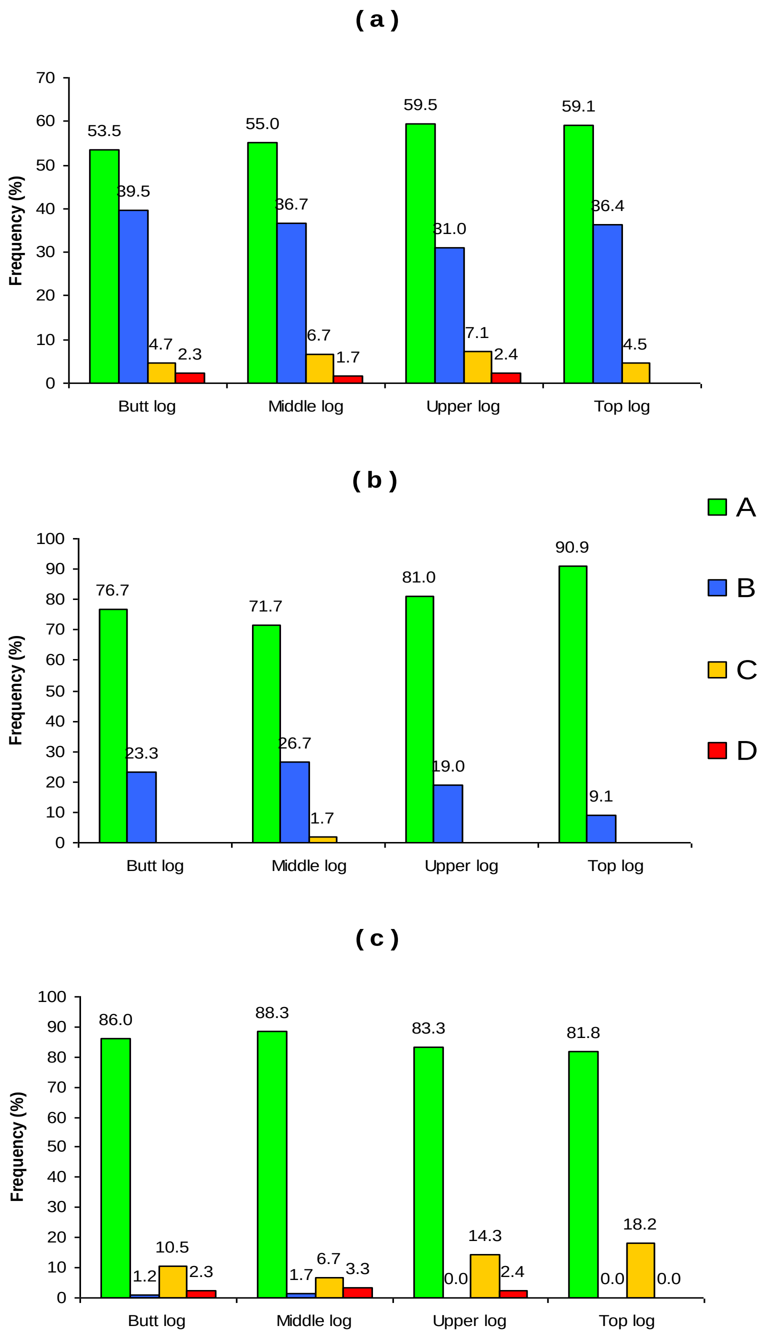


Figure 5-4: Effects of stem height of each type of timber distortion, (a) spring, (b) bow and (c) twist

Figure 5-4 shows the effect of stem height on each type of timber distortion, spring, bow and twist. As all the timbers were kiln-dried with top-load method, timber distortion should be restrained in certain extent thus the influence of stem height could be reduced. For spring and bow, the percentage of Grade A samples seemed to slightly increase with the increasing of stem heights. However, the variation is not significant although this trend can be related to the distribution of shrinkage values along the tree height which was previously discussed in Chapter 3 (see Figure 3-9). Johansson (2002) reported that large longitudinal shrinkage on one edge face of a stud would result in spring and bow towards the side with less longitudinal shrinkage.

It can be seen in Figure 5-4, the twist results of Douglas-fir timber showed very little variation with log height position, along longitudinal direction. In the study of distortion of Norway spruce timber, Johansson and Kliger (2001) also reported that growth ring curvature and spiral grain angle together explained about 70% of the variation in twist. However, as the limitation of accessible information on spiral grain angle of Douglas-fir, this founding was unable to be verified in this study.

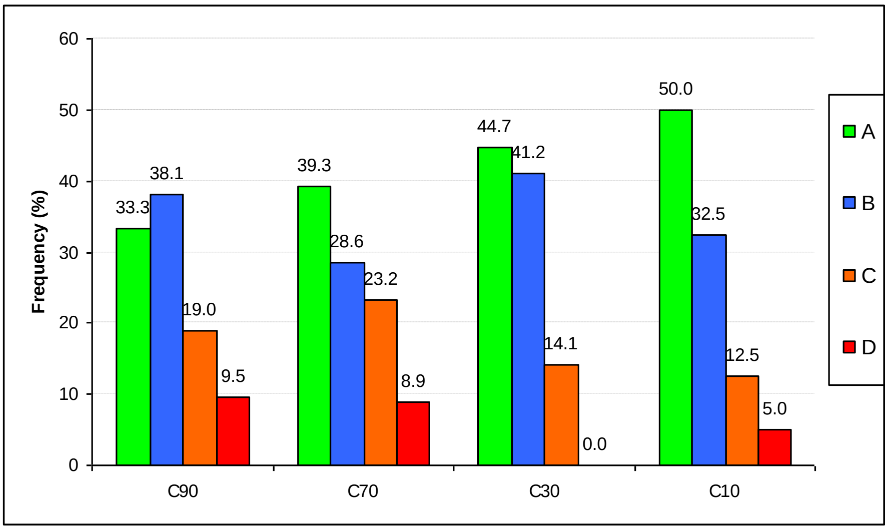


Figure 5-5: Influence of corewood proportion on timber distortion

Figure 5-5 is showing the variation of timber distortion result as a function of corewood proportion. Firstly, we can see that the yield of Grade A timbers increased with decreasing of the corewood proportion, with Grad A accounting for 33.3%, 39.3%, 44.7% and 50% for corewood proportion of 90% (C90), 70% (C70), 30% (C30) amd 10% (C10). More down-grade (Grade C and D) timbers (about 30%) were generated in high corewood proportion section such as C90 and C70.

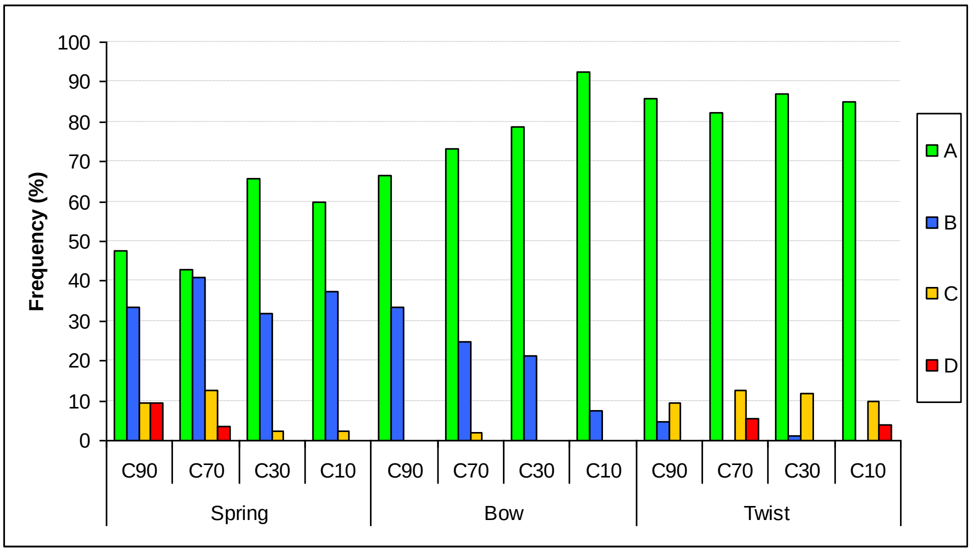


Figure 5-6: Corewood effect on spring, bow and twist

Figure 5-6 shows the influence of corewood proportion on spring, bow and twist. The results confirmed that timber quality degradation caused by the distortion worsened with the increase of corewood proportion. For spring, high rejection rate was found in high corewood proportion group C90 and C70. Almost 100% of the timber from low corewood proportion group of C30 and C10 fell into high grading classes, Grade A and Grade B. For bow, a clear correlation was also observed between timber quality and its corewood proportion. When corewood proportion was reduced, the percentage of Grade A timbers increased. It seems that spring and bow correlated to the corewood proportion with high level of significance while twist does not show the obvious correlation. Woxblom (1999) reported that twist was highly correlated to the proportion of corewood in the stud, distance from pith and grain angle. However, Douglas-fir in this study does not show such correlation.

Table 5-4: Number of each grade timber for Douglas-fir trees

Douglas-fir tree IDs	S1	S3	S8	S9	S10	S11	S12	S13	S14	SUM
A	15	2	18	2	5	10	0	11	26	89
B	7	1	16	6	8	10	5	10	17	78
C	3	14	0	5	1	0	2	3	6	34
D	0	4	0	3	0	0	1	0	1	9
SUM	23	21	34	16	14	20	8	24	50	210

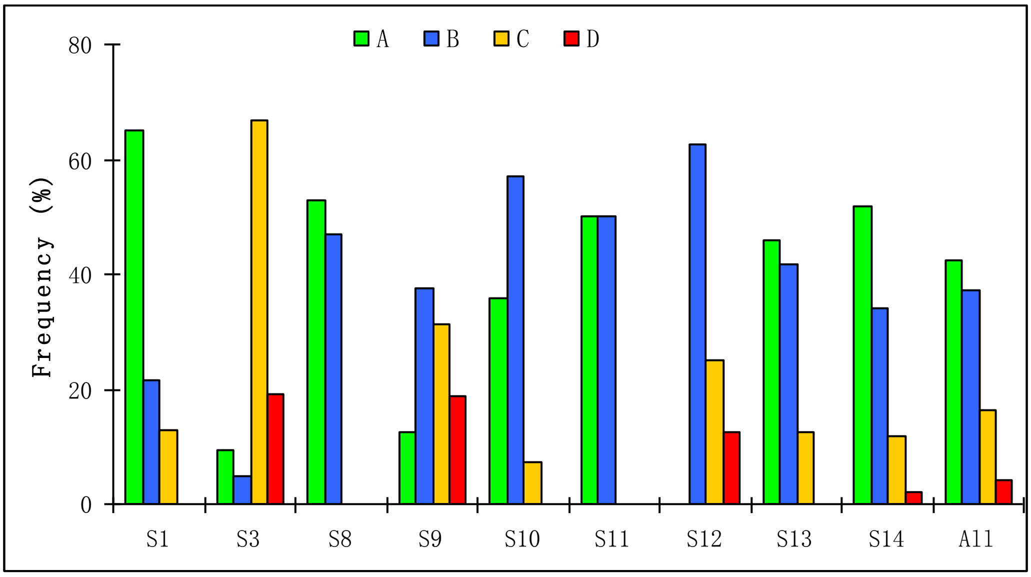


Figure 5-7: Variation of drying distortion between trees

Table 5-4 and Figure 5-7 show the timber distortion result from each Douglas-fir tree. Totally 210 pieces of Douglas-fir timbers were produced from 9 trees. It was found that distortion varied significantly between trees. Timbers from trees S8 and S11 showed excellent shape stability with all of the timber falling into Grade A and Grade B while timbers from tree S3 had significant distortion with more than 85% of the timbers falling to Grade C (67%) and Grade D (19%). Tree S3 itself contributed 42% of the Grade C and D result of all Douglas-fir logs. The reason of this between-tree variation could be the difference of physical properties between trees which was found in previous Chapter 3.

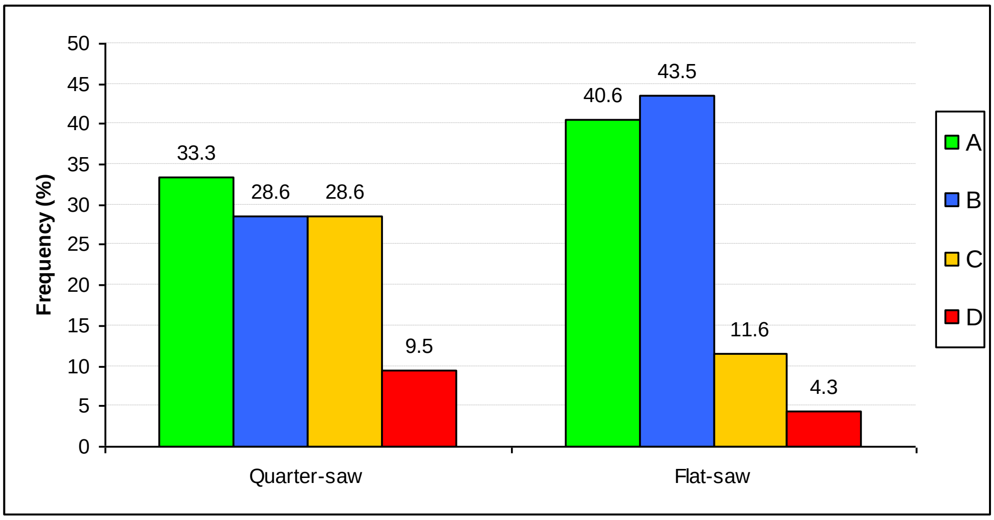


Figure 5-8: Variation of distortion result on sawing pattern

Figure 5-8 illustrates the distortion result of Douglas-fir timbers from different sawing patterns. It is quite clear that timbers with quarter-saw pattern tended to generate higher distortion board than those with flat-saw pattern. The proportion of Grade C and Grade D timbers produced from quarter-saw pattern were 28.6% and 9.5%, while the corresponding values from flat-saw pattern were only 11.6% and 4.3%.

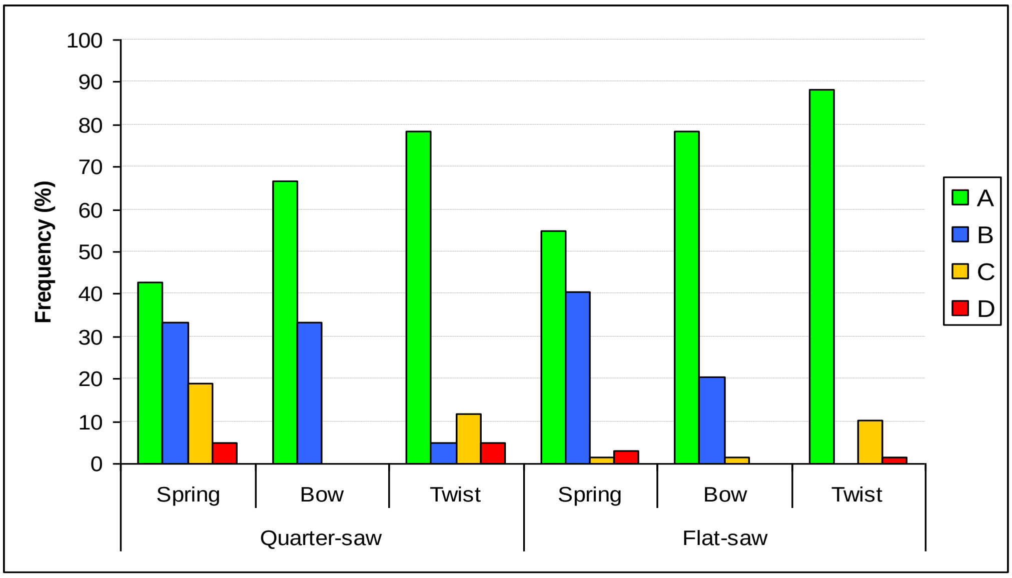


Figure 5-9: Sawing pattern effect on spring, bow and twist

In Figure 5-9, distortion result of spring, bow and twist with respect to the different sawing pattern was compared. For Douglas-fir, the flat sawn pattern seems to generate more Grade A boards with the three types of distortion. However, less Grade B boards were produced with the flat sawn pattern based on bow and twist. Woxblom (1999) reported that the sawing pattern greatly affected the geometrical properties of the studs after drying. Especially twist was influenced by sawing pattern. In this study, spring is considered to be influenced most by sawing patterns, as it can be seen that about 23.8% of Grade C and D boards were produced with the quarter-saw pettern, while there were only 4.3% Grade C and D boards from flat-saw pattern.

5.3 Acoustics properties and its related mechanical properties of Douglas-fir

5.3.1 Acoustic properties of Douglas-fir

As mentioned previously in Chapter 2, an acoustic analysis tool, Director HM200, was used in this study to assess mechanical properties of green log and kiln-dry timbers. Acoustic velocity of 31 Douglas-fir logs was taken after felling, and acoustic velocity of each 4.8 meters long timber was taken before and after timber drying. The acoustic MOE (GPa) was determined from the acoustic velocity by using the following equation (Wang 2005, 2006; Grabianowski 2006; Bucur 2006):

$$\mathrm{MOE} = \rho \times V^2$$

Where ρ (kg/m^3) is the density of the board and V (m/s) is the measured acoustic velocity (the wave speed). Acoustic MOE is often used as an estimate of the static MOE of a board (Wang, 2006).

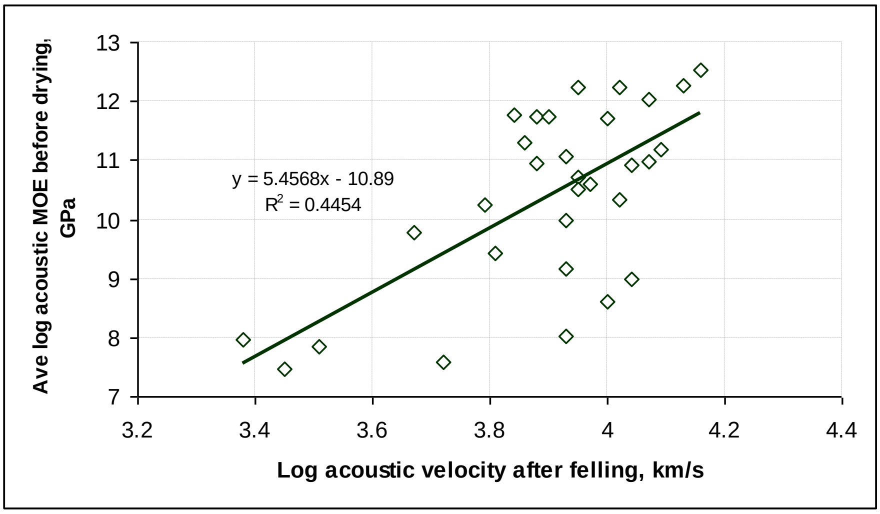


Figure 5-10: Average log acoustic MOE as a function of log acoustic velocity for Douglas-fir wood

In the analysis, the average acoustic MOE for all timber from one log is termed as the log acoustic MOE and is compared with the log acoustic velocity of the same log after felling (Figure 5-10). From Figure 5-10, a significant relationship (R=0.67) was observed between log acoustic MOE and acoustic velocity. It was shown that acoustic velocity could provide effective method for segregation of stiffness classes of Douglas-fir logs.

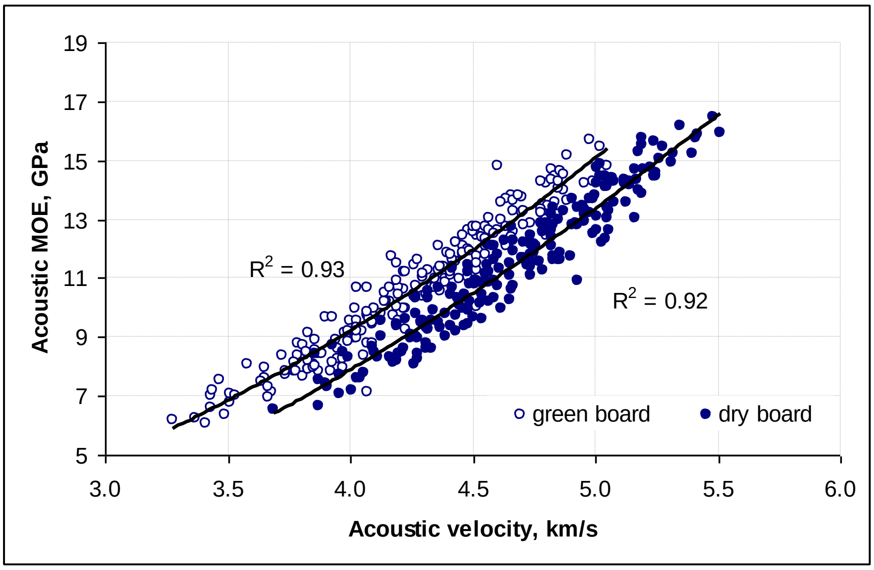


Figure 5-11: Relationship between board acoustic MOE and acoustic velocity before and after timber drying

Figure 5-11 shows the relationship between timber acoustic MOE and acoustic velocity both in green and kiln-dry condition. It is very obvious that there is a strong positive correlation between board acoustic MOE and acoustic velocity. For green board, the R^2 value between acoustic MOE and acoustic velocity was 0.93. The corresponding value for dry board was 0.92.

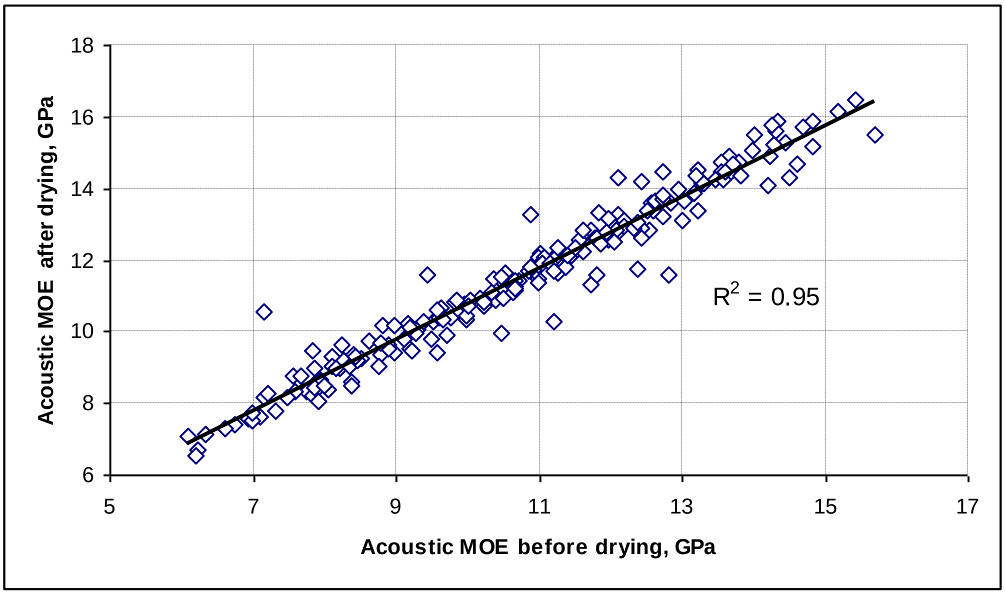


Figure 5-12: Correlation of acoustic MOE of Douglas-fir timbers before and after drying

Most wood properties change with moisture content when the moisture content is below fibre saturation point (Tsoumis 1991). The fibre saturation point of Douglas-fir measured in this study was 24.5%MC. After timbers were dried to a target MC of 18% and then were equalised to an average value of 15%, it was expected that some mechanical properties would change. The results show that timber acoustic MOE value increased after timber drying. However, the dry timber MOE is also strongly related to its green MOE as shown in Figure 5-12 in which a high correlation (R^2 =0.95) was observed between timber green acoustic MOE and dry MOE. Therefore, the acoustic MOE value measured in green board could largely represent its kiln-dry acoustic MOE result at the same final MC.

5.3.2 Acoustic MOE results of Dougas-fir

The resulting distribution of acoustic MOE of Douglas-fir timbers is shown in Figure 5-13. At average MC of 15.43%, the average acoustic MOE of 210 Douglas-fir timbers was 11.52GPa with more than 90% of the values falling in a range of 9 and 16GPa. Walford (1985) reported that the static MOE of 64-year-old New Zealand grown Douglas-fir was 10.19GPa. The acoustic MOE value measured from this study is higher than the reported static MOE value.

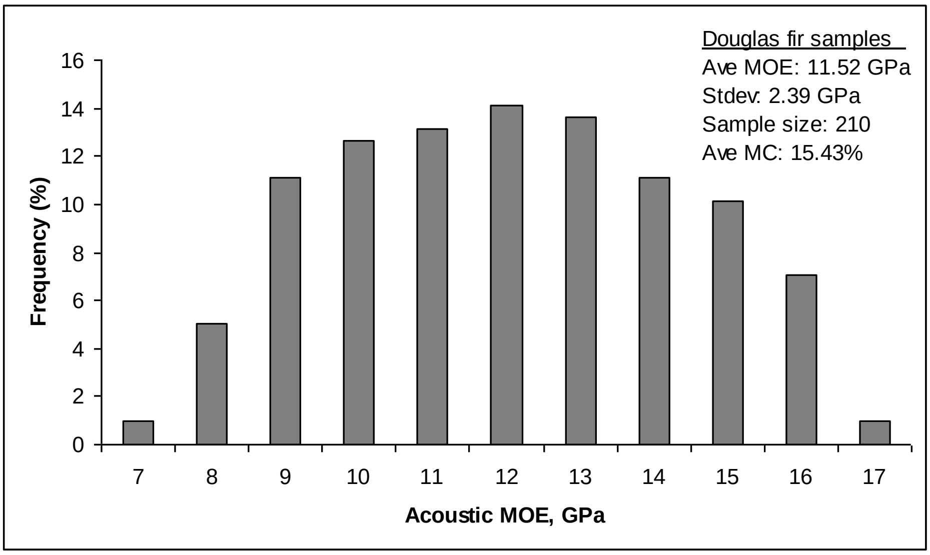


Figure 5-13: Distribution of acoustic MOE of Douglas-fir timbers

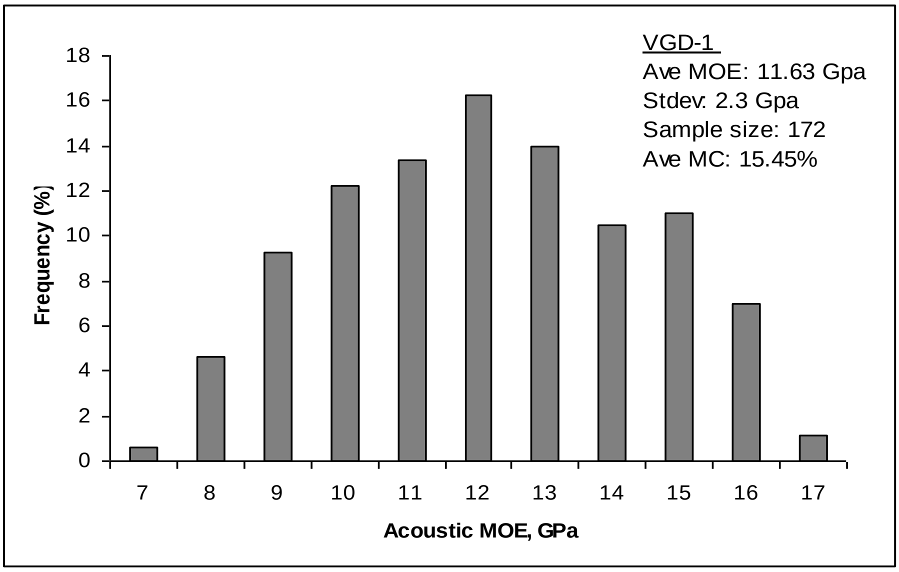


Figure 5-14: Distribution of Acoustic MOE of VGD-1 Douglas-fir timbers

Figure 5-14 shows the MOE distribution of No.1 framing (VGD-1) timbers. More than 85% of Douglas-fir timbers were visually graded as VGD-1 timber. The average acoustic MOE of VGD-1 timber was 11.63GPa and 95% of the result distributed between 9 and 16GPa.

5.3.3 Variation of acoustic properties with corewood proportion

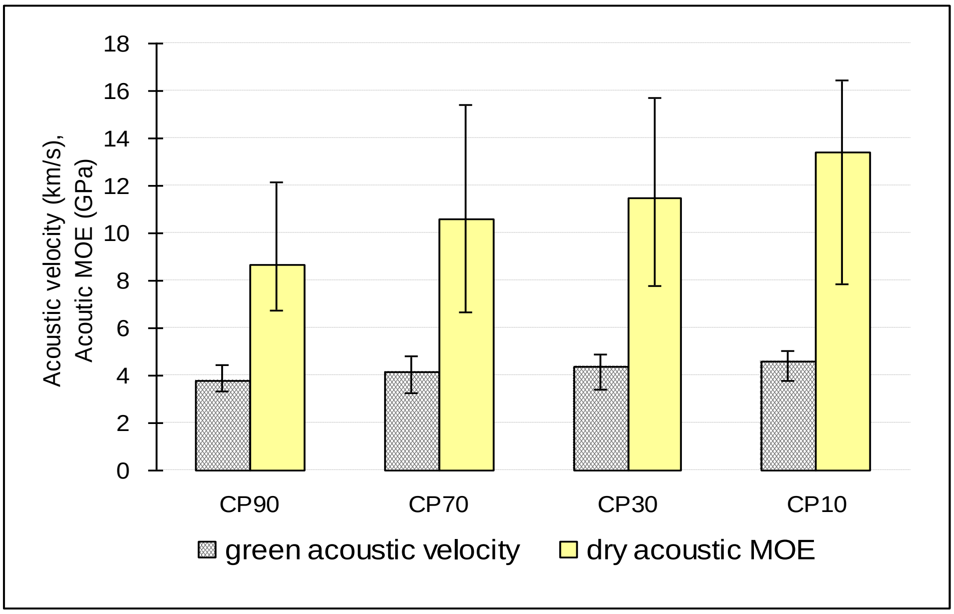


Figure 5-15: Variation of acoustic properties on corewood proportion

Influence of corewood on both the green acoustic velocity and dry acoustic MOE is shown in Figure 5-15, and the error bars show the maximal and minimal values. It can be seen that corewood proportion had significant effect with an increasing trend being observed with decreasing of the corewood proportion for both of these acoustic properties. The mean value of the green acoustic velocities were 3.79km/s, 4.14km/s, 4.35km/s and 4.56km/s for boards with corewood proportions of 90% (C90), 70% (C70), 30% (CP30) and 10% (CP10), respectively. The corresponding average acoustic MOE values were 8.16GPa, 9.85GPa, 10.73GPa and 12.15GPa, respectively.

5.3.4 Acoustic properties compared with distortion grade

In order to determine the relationship between acoustic properties and timber distortion during kiln drying, the variation of average value of acoustic velocity and average acoustic MOE are linked to the timber distortion grade as given in Table 5-5.

In Table 5-5, the average green acoustic velocity values were 4.39km/s for Grade A timbers, 4.21km/s for Grade B, 4.12km/s for Grade C and 4.01km/s for Grade D. The corresponding results for dry acoustic MOE were 12.35GPa, 11.17GPa, 10.21GPa and 10.11GPa, respectively. For Douglas-fir timbers, the average value for both green acoustic velocity and dry acoustic MOE decreased consistently as the degree of timber distortion increased. In another words, acoustic properties can not only be used as an effective surrogate measure of stiffness, but can also be applied to predict warp-prone timbers in some special requirements of end-user.

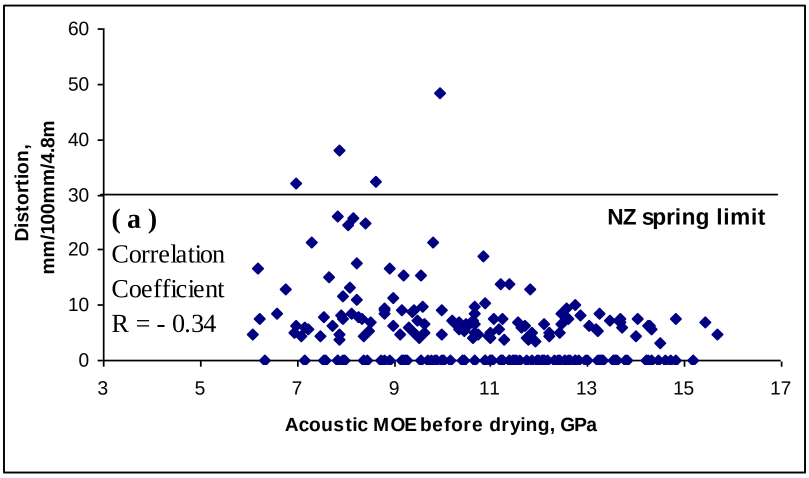
Table 5-5: Variation of acoustic properties with distortion grading

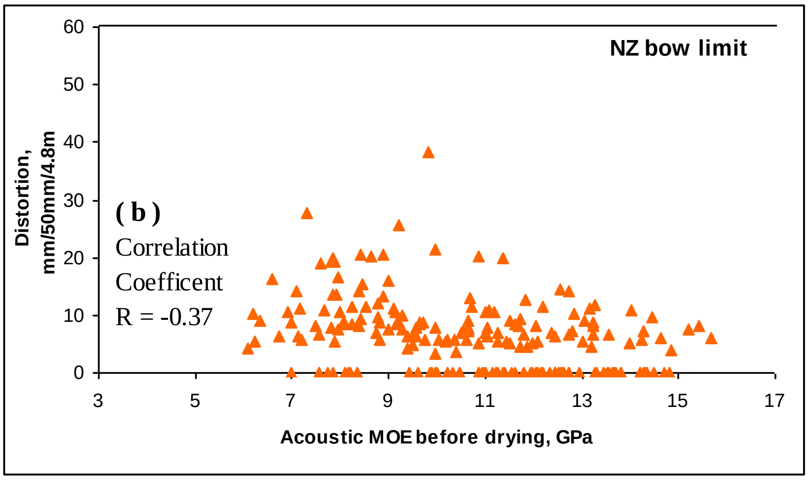
Distortion	No. of	Green acoustic velocity, km/s				Dry acoustic MOE, GPa			
Grade	samples	Ave	Stdev	Max	Min	Ave	Stdev	Max	Min
A	89	4.39	0.35	4.98	3.41	12.35	2.19	19.40	7.07
B	78	4.21	0.40	5.02	3.37	11.17	2.37	16.47	6.68
C	34	4.12	0.43	5.05	3.28	10.21	2.95	16.16	0.36
D	13	4.01	0.31	4.62	3.53	10.11	1.68	13.09	7.52

5.3.5 Acoustic MOE compared with spring, bow and twist

Figure 5-16 presents the correlation between green acoustic MOE result and distortion of Douglas-fir timbers, in forms of bow, spring and twist. A significant negative association was observed between the acoustic MOE and two forms of distortion of spring ($R = -0.34$) and bow ($R = -0.37$). Both spring and bow decreased when acoustic MOE increased, the high distortion timbers were often found in the lower stiffness boards with acoustic MOE value less than 10GPa. The correlation between green MOE and twist was not clearly observed.

Wang (2006) found similar relationship between acoustic MOE and mean warp results for Ponderosa pine, in which significant correlation was observed between acoustic MOE and two forms of distortion – crook and bow, but no significant relationship was found for the twist. The results from this study indicate that acoustic velocity of green boards has great potential to be used as pre-sorting criteria to identify warp-prone boards before kiln-drying.





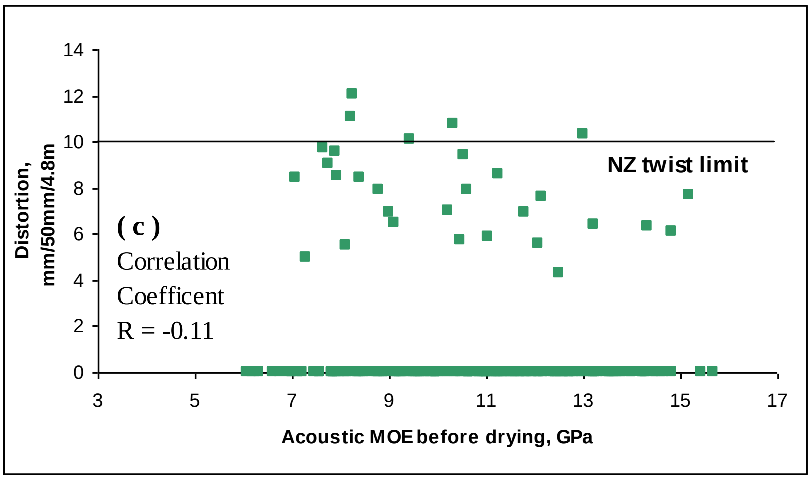


Figure 5-16: Correlation of acoustic MOE with (a) spring, (b) bow and (c) twist

Chapter 6 . Distortion and Mechanical Properties of Radiata pine

Timber dimensional stability and shape stability of New Zealand radiata pine were studied in this chapter. Within tree and between trees variations of timber distortion were investigated. The influence of sawing patterns and corewood proportion on the timber distortion was discussed. Timber mechanical properties and its related acoustics properties with the relationships of timber distortion were analysed.

6.1 Dimensional stability of radiata pine full-sized timber

In timber sawing, 178 boards were produced from thirteen, 27-year-old radiata pine trees. All these boards were visually graded (VGD) into VGD-1, VGD-2 and VGD-B according to AU/NZ visual grading standard (NZS 3631:1988). The results from the VGD are given in Table 6-1, from which it can bee seen that 47.8% of radiata pine timbers were visual graded as high stiffness class timber (VGD-1), 34.8% were graded into VGD-2 and 17.4% of the radiata pine timber were visually rejected (VGD-B).

Table 6-1: Visual grading of radiata pine samples

Visual grade	No. of Samples	Frequency (%)
VGD-1	85	47.8
VGD-2	62	34.8
VGD-B	31	17.4

All samples were weighted before and after drying to calculate MC changes at each stage. As previously described in Chapter 5, green moisture content of each radiata pine board was derived from an estimated oven-dry weight which was determined from the moisture meter reading after drying. The deviation (1.6%) of the meter reading to actual MC value of radiata samples was determined through 10 test samples by oven dry method.

Table 6-2: Shrinkage distribution of radiata pine full-sized timber

Group	Flat-sawn timber			Quarter-sawn timber		
	MC (%)	TS (%)*	RS (%)**	MC (%)	TS (%)*	RS (%)**
C90	10.8(0.74)	1.89(0.54)	1.76(0.40)	11.3(0.31)	2.01(0.71)	1.88(0.23)
C70	11.1(0.70)	2.23(0.39)	2.17(0.39)	11.4(0.66)	1.84(0.23)	1.73(0.25)
C30	11.5(1.09)	2.40(0.48)	2.22(0.42)	12.0(0.09)	1.90(0.54)	1.78(0.56)
C10	11.1(0.66)	2.82(0.53)	2.35(0.56)	11.2(0.12)	2.20(0.27)	1.70(0.20)

**TS: Tangential shrinkage* ***RS: Radial shrinkage*

Note: Numbers in brackets are standard deviation.

Dimensions were measured in board width, thickness and length thus to determined the shrinkage in longitudinal, tangential and radial directions. In the same way as for the Doulas-fir boards, the longitudinal shrinkage is the board length shrinkage while the tangential shrinkage is the width shrinkage for flat sawn boards and is the thickness shrinkage for the quarter sawn boards. Correspondingly, the radial shrinkage is the thickness shrinkage for the flat sawn boards and is the width shrinkage for the quarter sawn boards. Table 6-2 shows the distribution of shrinkage values of radiata pine samples as a function of corewood proportion. Similar to the result obtained from Douglas fir samples, flat-sawn radiata pine timber showed higher value in its tangential and radial shrinkage with lower corewood proportion. This trend was consistent with the results found in small clear sample studies as presented in Chapter 4, in which the outer parts of a stem appeared to have greater tangential and radial shrinkage values than the corewood.

Average tangential shrinkage and radial shrinkage obtained from full-size radiata pine samples were both 2.16% and 1.95%, respectively, at 11.5% MC. Further examination found that the tangential and radial shrinkage was higher in flat sawn board than that in the quarter sawn boards. Although the tangential shrinkage was higher than the radial shrinkage in general, the difference was much less than that found from small clear samples in which studies the tangential and radial shrinkage was 2.94% and 1.37% at 12.1% MC.

6.2 Shape stability of radiata pin full-sized timber

6.2.1 Drying distortion results and classification of radiata pine samples

Distortion of radiata pine timber was measured after drying. Distortion grades in each individual form (spring, bow and twist) were introduced in Chapter 5 (Table 5-3) and the same standard was used for radiata pine. Timber with Grade A has first-rate shape stability while timber with Grade D shows excessive distortion which should be rejected.

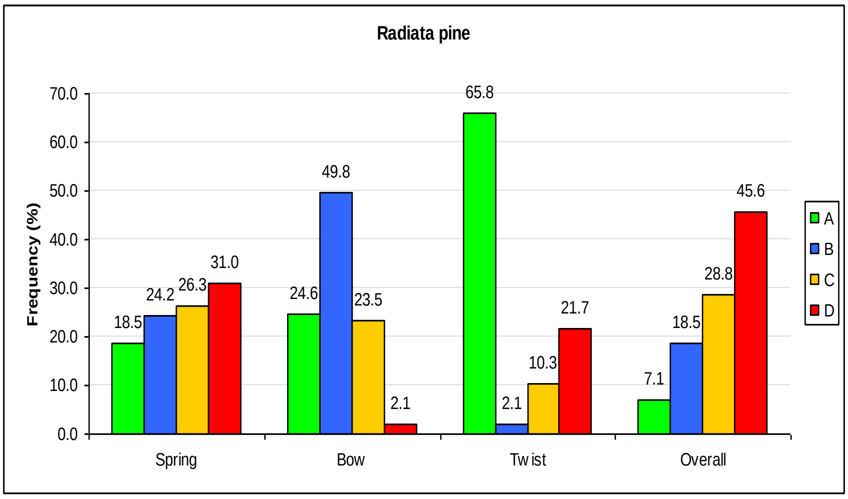


Figure 6-1: Distribution of distortion grades of dry radiata pine timber

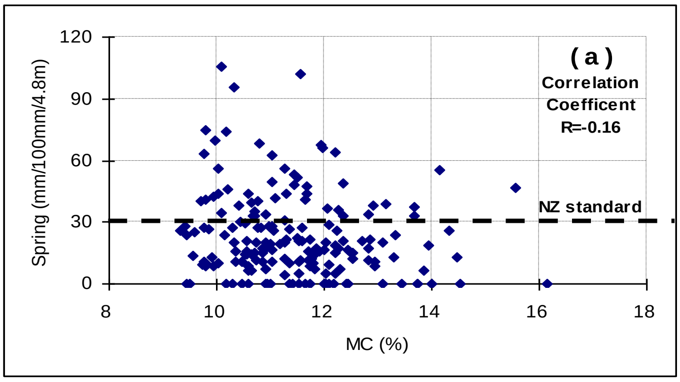
The overall distortion results of 100mm × 50mm × 4.8m radiata pine timber were described in Figure 6-1. Spring and twist were the main reasons to cause timber rejection, bow was not showing to be an issue of timber rejection based on NZ timber grading rules (*NZS 3631*: 1988). For spring, the percentage of distortion results for Grade A (≤5mm), Grade B (5~15mm), Grade C (15~30mm) and Grade D (≥30mm) were 18.5%, 24.2%, 26.3% and 31%. Those results for twist were 65.8%, 2.1%, 10.3% and 21.7% respectively. Spring caused 68.0% of rejection and twist caused 47.6%. Among all the rejected timbers, about 20% had shown more than one type of excessive distortions.

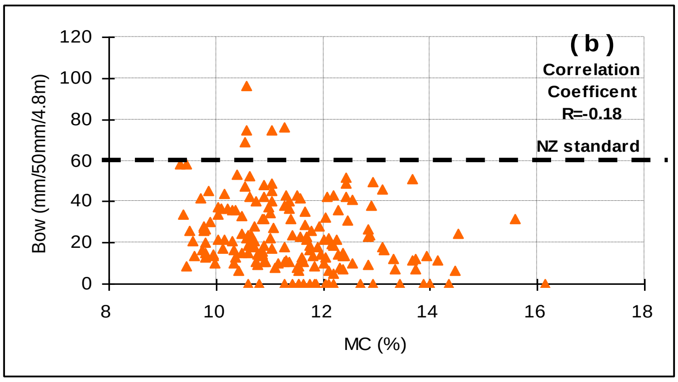
Haslett (1991) reported that twist was the most serious distortion concern for 25-year-old radiata pine during high temperature drying. However, spring was the most significant factor in this study which may be attributed to lower corewood proportion in the logs selected. The logs grown in South Island are generally smaller and thus contain less corewood than logs in North Island in New Zealand. In addition, the lower temperature drying may also generate less excessive twist boards with weight restraint on the stacks during kiln drying. Oja (2006) reported that timbers in upper part of the stack had greater twist than those in lower part due to the difference in the constraint load.

6.2.2 Factors affecting the drying distortion of radiata pine timbers

Figure 6-2 shows the relationship between final MC and timber distortion in forms of spring, bow and twist. After timber drying, the MC of radiata pine boards was found to be much higher than the target MC of 12%, and distributed very unevenly. Therefore, these boards were moved to a dehumidifier kiln and seasoned for 2 more days. After equalisation, the final MC of radiata pine timbers reached a mean value of 11.54% with a standard deviation of 1.17%.

With a rejection cutting line in the figure, it can be seen clearly that spring and twist are responsible for the timber rejection under NZ standard. A significant correlation (R= - 0.39) was observed between timber final MC with twist, but the correlation was less obvious for spring (R= - 0.16) and bow (R= - 0.18). It was reported by Haslett (1991) that twist was directly related to MC with every 1% reduction in MC giving an average increase twist of 0.6mm. This was confirmed in this study as excessive timber distortion was more frequently found with lower final MC (≤ 12%MC). This discontented result could be easily avoided by the improvement of drying schedule.





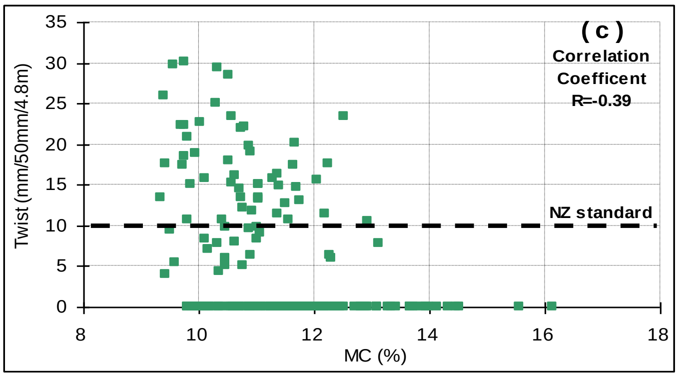


Figure 6-2: Drying distortion as a function of final MC, (a) spring, (b) bow and(c) twist

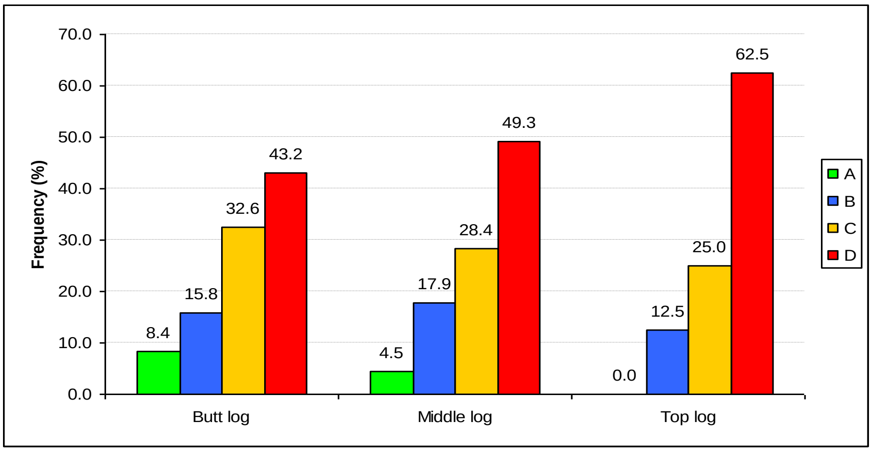


Figure 6-3: Influence of stem height on the timber distortion grade

Figure 6-3 shows the distribution of timber distortion of radiata pine as a function of stem height. As discussed in Chapter 5, the board grade will be determined by the lowest grade in the three distortion forms. In Figure 6-3, the Grade A requires the boards to have Grade A result in all spring, bow and twist. From the figure, the timber rejection (Grade D) increased with the increasing of stem height. The percentage of Grade D timbers received from top log was almost 20% higher than those from butt log, and the most significantly there was no Grade A radiata pine timbers generated from the top log.

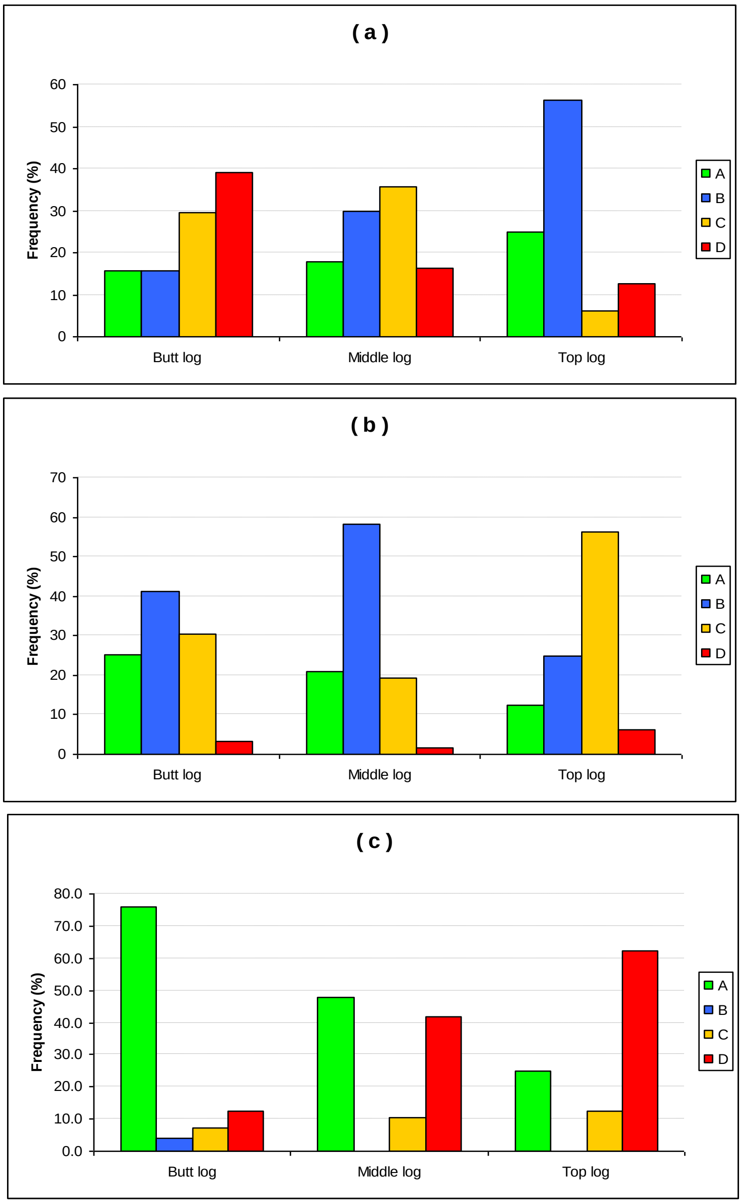


Figure 6-4: Influence of log height on (a) spring, (b) bow and (c) twist

The influence of stem height on individual distortion type was clearly shown in Figure 6-4. As the main reasons of timber rejection of radiata pine in this study, spring and twist showed opposite trend for the influence of stem height. For spring, the percentage of rejected timber declined dramatically from 39.0% of butt log to16.4% of middle log, and to 12.5% of the top log. The greater rejection rate obtained from butt log could be caused by the excessive longitudinal shrinkage value at the bottom of stem (see Figure 4-6 in Chapter 4). As a major effect of twist, spiral grain angle increase significantly with height in the stem (Cown, 1991; Young, 1991), therefore, the refection due to excessive twist significantly increased with increasing of stem height. The same finding was also report by Haslett (1991) that logs from higher positions produced timber with significantly more twist. Comparatively higher rejection rate of bow was also found in the top log than it from other heights, but the reason of this was not clear.

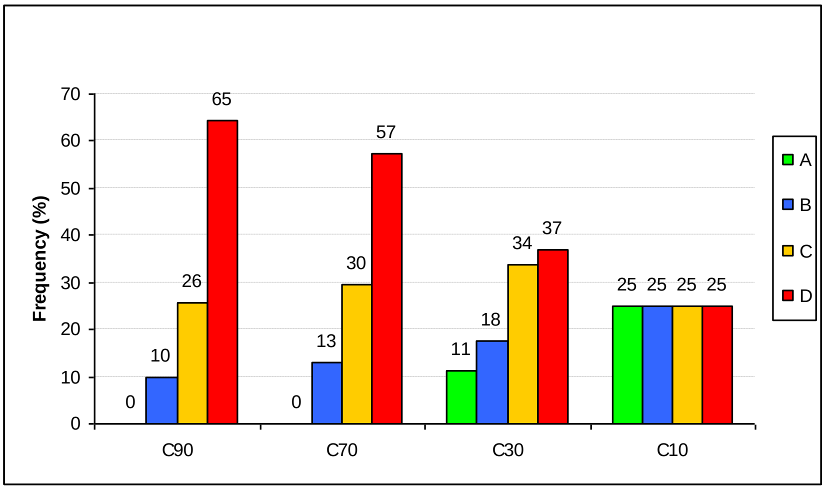


Figure 6-5: Variation of timber distortion grade on corewood proportion

Figure 6-5 shows the variation of distortion results as a function of corewood proportion. A clear trend is shown that rejection rate (Grade D) dropped significantly with decreasing of the corewood proportion in each board whereas the percentage of high grade timber (Grade A and B) increased gradually when the corewood proportion decreased from 90% (C90) to less than 10% (C10).

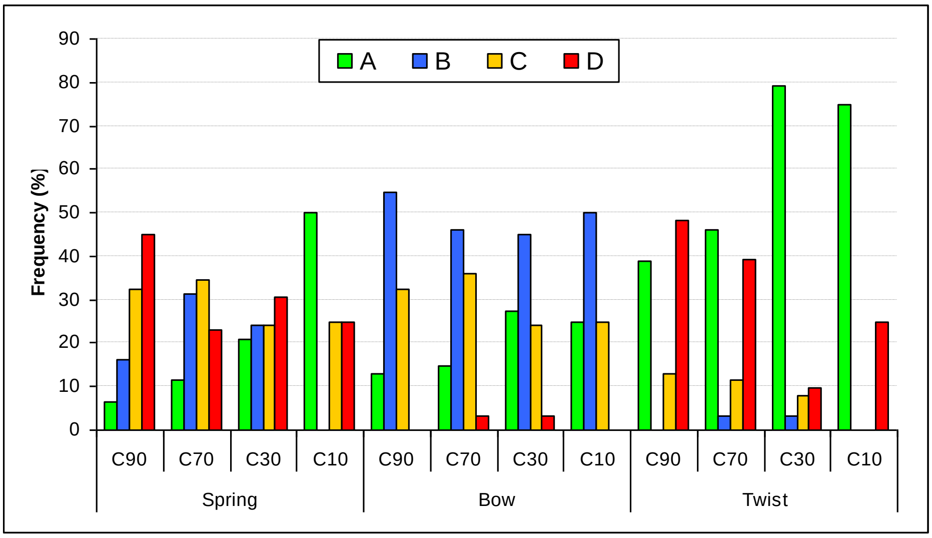


Figure 6-6: Influence of corewood proportion on spring, bow and twist

The influence of corewood proportion on timber distortion in forms of spring, bow and twist is presented in Figure 6-6. To certain extent, the corewood proportion has significant effect on all types of timber distortions, especially, for spring and twist. The boards produced from or close to corewood zone (group C90 and C70) appeared to have much higher deformation than those sawn away from pith (group C30 and C10). The reason for excessive twist in the corewood zone of radiata pine is generally agreed to be the greatest microfibril angle and spiral grain angle near the pith (Cown, 1991; Haslett, 1991; Young, 1991). The excessive spring could be related to high longitudinal shrinkage variation within the corewood which was obtained from small sample study in Chapter 4. Corewood effect on bow was not clearly observed in this study.

Table 6-3: Number of each grade timber for different radiata pine trees

Radiata pine tree IDs	**L1**	**L2**	**L3**	**L4**	**L5**	**L6**	**L7**	**L8**	**L9**	**L10**	**L11**	**L12**	**L13**	SUM
A	2	1	1	6	0	0	0	0	0	0	0	0	1	11
B	3	2	0	12	1	1	1	1	3	1	1	0	3	29
C	4	2	3	11	2	5	2	3	2	4	6	4	6	54
D	9	6	3	0	5	12	8	2	8	3	7	10	11	84
SUM	18	11	7	29	8	18	11	6	15	6	14	14	21	178

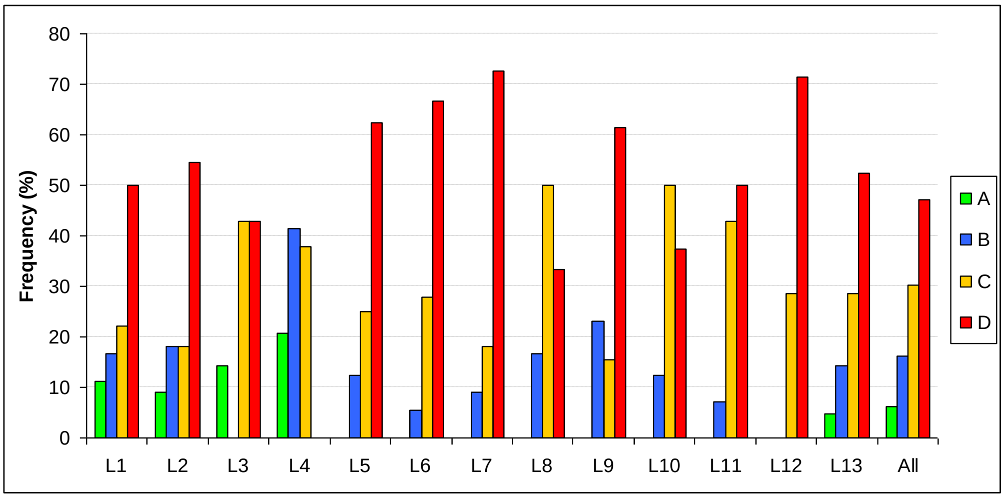


Figure 6-7: Variation of timber distortion grade between trees

Figure 6-7 and Table 6-3 show the timber distortion result from each radiata pine tree. Totally, 178 piece of radiata pine timber were generated from 13 radiata pine trees. In this study, radiata pine timber performed poorly with its shape stability during drying. Almost 50% of the boards were found to have extreme distortion beyond NZ acceptable distortion limit and thus were rejected from structure timber. The distortion varied significantly between radiata pine trees, timbers from tree L4 showed the good stability performance with the 21% Grade A, 41% Grade B and 38% Grade C. It is most noticeable that for radiata pine, most of the trees did not produce Grade A timber and small proportion of Grade B timber, especially for tree L5, L6, L7, L9 and L12 with the worst rejection rate over 60%. The between-tree variation in the distortion is related to the variations of shrinkage characteristics as well as other properties such as spiral grain angle. Cown (1992) reported that the spiral grain angle varied greatly between trees for radiata pine.

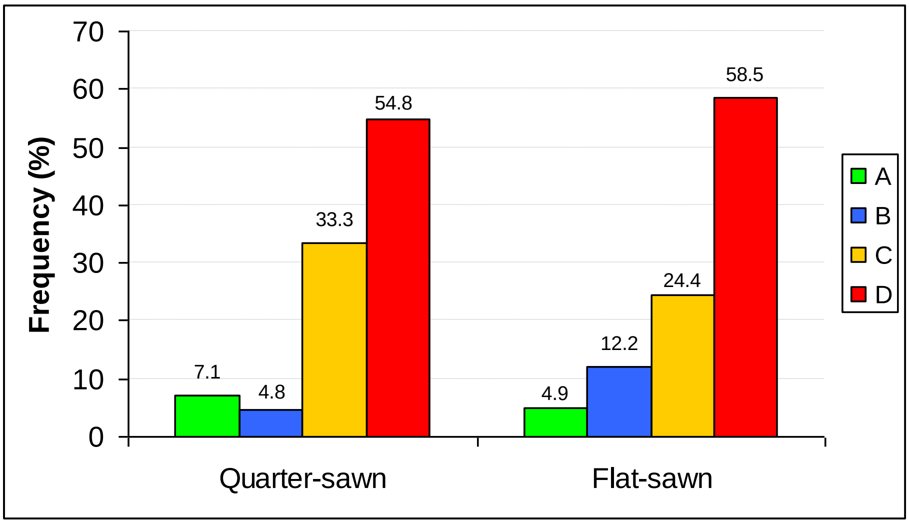


Figure 6-8: Comparison of distortion between quarter-sawn and flat-sawn timbers

In total, 31 radiata pine logs were sawn by practical sawing method at sawmill. Flat-sawn and quarter-sawn timbers were identified base on their growth ring orientation pattern on cross section. Figure 6-8 shows the comparison of the distortion results between quarter-sawn timbers and flat-sawn timbers for radiata pine. The difference of drying distortion between quarter-sawn and flat-sawn radiata pine timbers is not significant. As mentioned in previous section, almost 50% of rejection was caused by twist which was not affected significantly by sawn patter. This finding could remove the influence of sawn pattern on timber distortion.

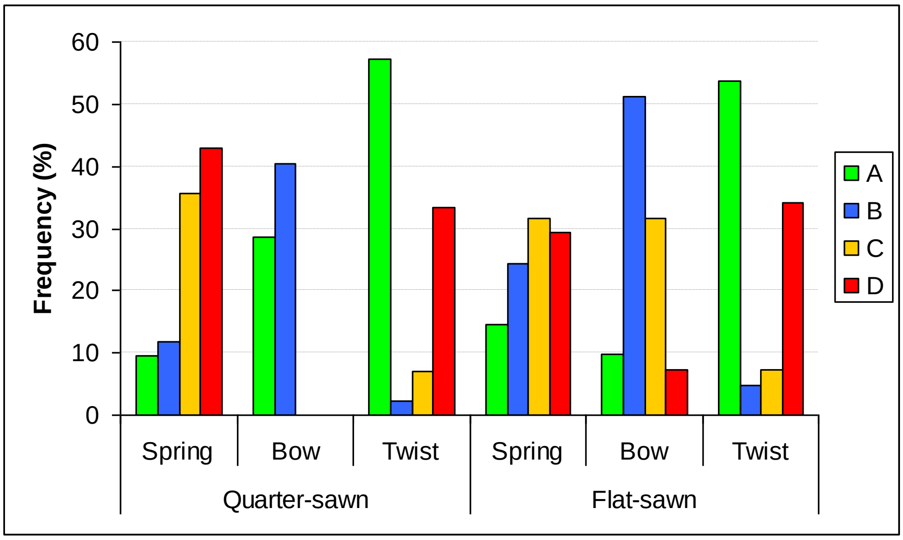


Figure 6-9: Influence of sawn pattern on spring, bow and twist

The comparison of sawn patterns effect on spring, bow and twist is shown in Figure 6-9. It is very obvious that the influence of sawn patterns on twist is insignificant, while the sawing pattern had major effect on spring and bow. Timbers in quarter-sawn tended to spring more than those in flat-sawn. The percentage of Grade C and Grade D timbers produced in quarter-sawn pattern were 36% and 43%, while the corresponding values in flat-sawn pattern boards were 30% and 29%. On the other hand, bow tended to be a big issue (32% of Grade C and 7% of Grade D) for flat-saws timbers, but it was not a concern for quarter-sawn boards. Haslett (1991) pointed out that longitudinal shrinkage manifests itself as crook (spring) in quarter-sawn and bow in flat-sawn lengths.

6.3 Acoustics properties and its related mechanical properties of radiata pine

6.3.1 Acoustic properties of radiata pine

Acoustic velocity value of 31 radiata pine logs was measured by Director HM200 after felling. The results varied between 2.66 and 3.84 km/s, with an average value of 2.92 km/s. After sawing, the acoustic velocity of each board was also measured using the above instrument. With the known origination of each board and its density, the acoustic MOE for each board was calculated in the same way as discussed in Chapter 5. Figure 6-10 shows the relationship between average acoustic MOE of each log (mean of all boards from one log) and log acoustic velocity. The relationship shown in the graph was poor (R = - 0.24) which could be caused by the variation of green wood density of radiata pine. From this finding, it seemed to be less reliable to use acoustic analysis tool alone, such as Director HM200, to pre-sort radiata pine log into different stiffness classes.

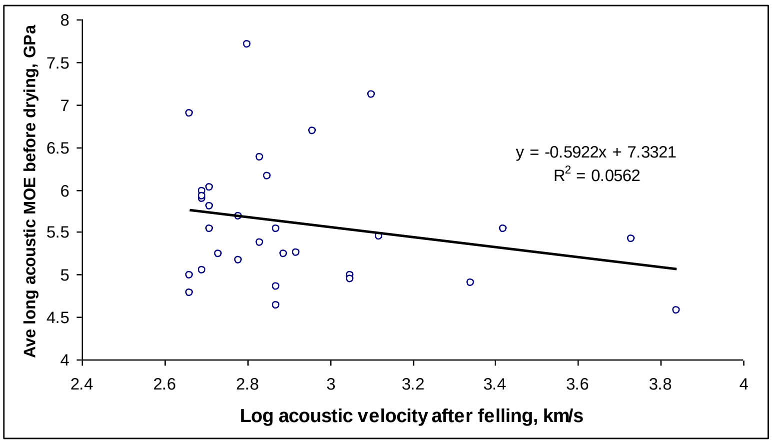


Figure 6-10: Average log acoustic MOE compared to log acoustic velocity for radiata pine wood

Grabianowski (2006) reported the significant correlation between time of flight (TOF) (another term for acoustic velocity) on the log and that in the outerwood boards of young radiata pine trees (aged 8-11), however, the TOF is likely to depend on the tree diameter and hence becomes less certain with increasing age. The age of radiata pine trees (aged 26) in this study is much older. Thus, this could also be the reason to cause the uncertainty in the correlation between log acoustic MOE and log green acoustic.

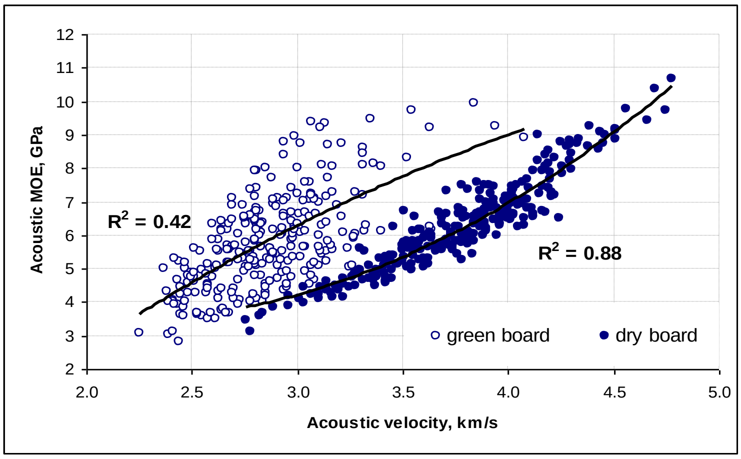


Figure 6-11: Relationship between board acoustic velocity and acoustic MOE before and after timber drying

The acoustic MOE of green and kiln-dried board was calculated from its density and acoustic velocity. Figure 6-11 plots the relationship between timber acoustic velocity and acoustic MOE both in green and kiln-dried condition. It can be seen that the correlation between acoustic velocity and stiffness in much better in kiln-dried board as the variation of wood density at kiln-dried condition is much less than when it is green.

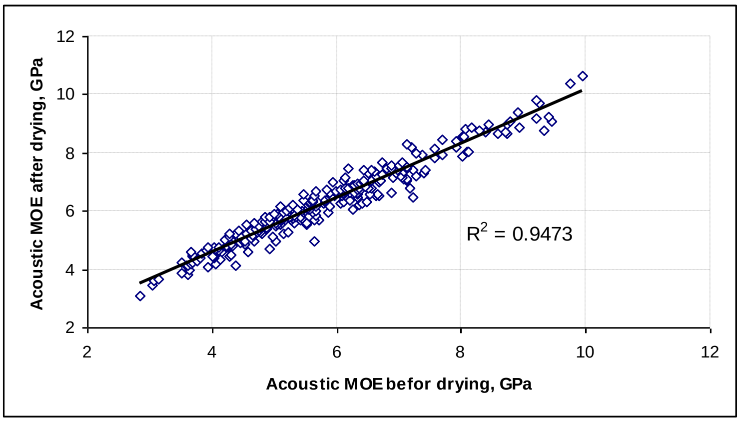


Figure 6-12: Correlation of acoustic MOE of radiata pine timbers before and after drying

However, a strong positive linear relationship ($R^2 = 0.95$) was observed between green and kiln-dried acoustic MOE for each board as shown in Figure 6-12. After all radiata pine timbers were kiln-dried, the average acoustic MOE value (6.27GPa) for all boards increased by 8.1% comparing to the green value (5.80GPa). This result indicated that the stiffness of boards in green condition could be used to predict the stiffness at dried condition (Carter, 2006). However, the acoustic velocity measurement alone is not sufficient to sort radiata pine timbers into different stiffness class.

6.3.2 Acoustic MOE results of radiata pine

In order to draw the ideal distribution trend of acoustic MOE for radiata pine timbers, additional 100 pieces of radiata pine timber were analysed together with 178 distortion samples. These added timbers were sawn in the same sawmill and the sawing process as for all selected test boards.

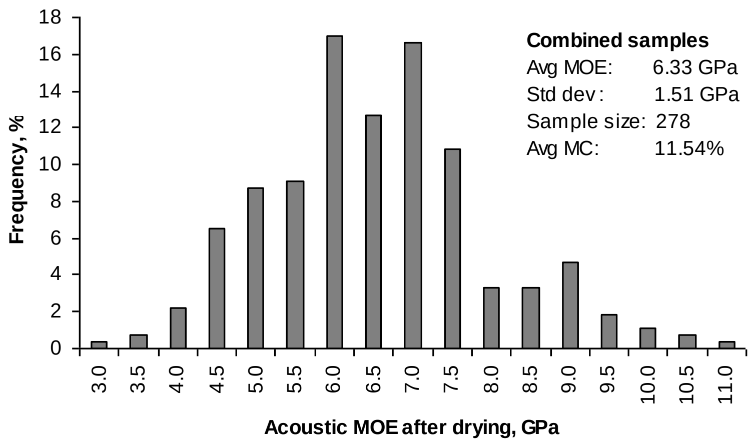


Figure 6-13: Distribution of acoustic MOE of radiata pine timbers

Figure 6-13 illustrates the distribution of acoustic MOE of kiln-dried radiata pine timbers. At final MC of 11.54%, the mean acoustic MOE of 278 radiata pine timbers was 6.33GPa (Standard deviation of 1.51GPa), more than 80% of the values fell in a range of 4.5 and 7.5GPa. Walford (1985) reported that the static MOE of 30-year-old New Zealand radiata pine was 8.2GPa. If the effect of crop age was excluded, the result from this study was close to this reported value.

After timber sawing, the total 278 pieces of radiata pine green boards (178 distortion samples plus 100 additional boards) were visually graded into 3 grading groups. The comparison of timber acoustic MOE distribution for each group is shown in Figure 6-14 (a) to Figure 14 (c). Boards with VGD-1 (Figure 4-14a) were found to be much stiffer than those of VGD-2 (Figure 6-14b) and VGD-B (Figure 6-14c). The acoustic MOE values of VGD-1 timbers were mainly (87%) distributed between 5.5 and 9GPa with average value of 6.83GPa. However, the average MOE values for VGD-2 (5.94GPa) and VGD-B (5.82 GPa) timbers were not significant. Nevertheless, the New Zealand visual grading rule is effective to select high class stiffness timbers, but the cutting for further segregation of timbers with lower stiffness is not very effective.

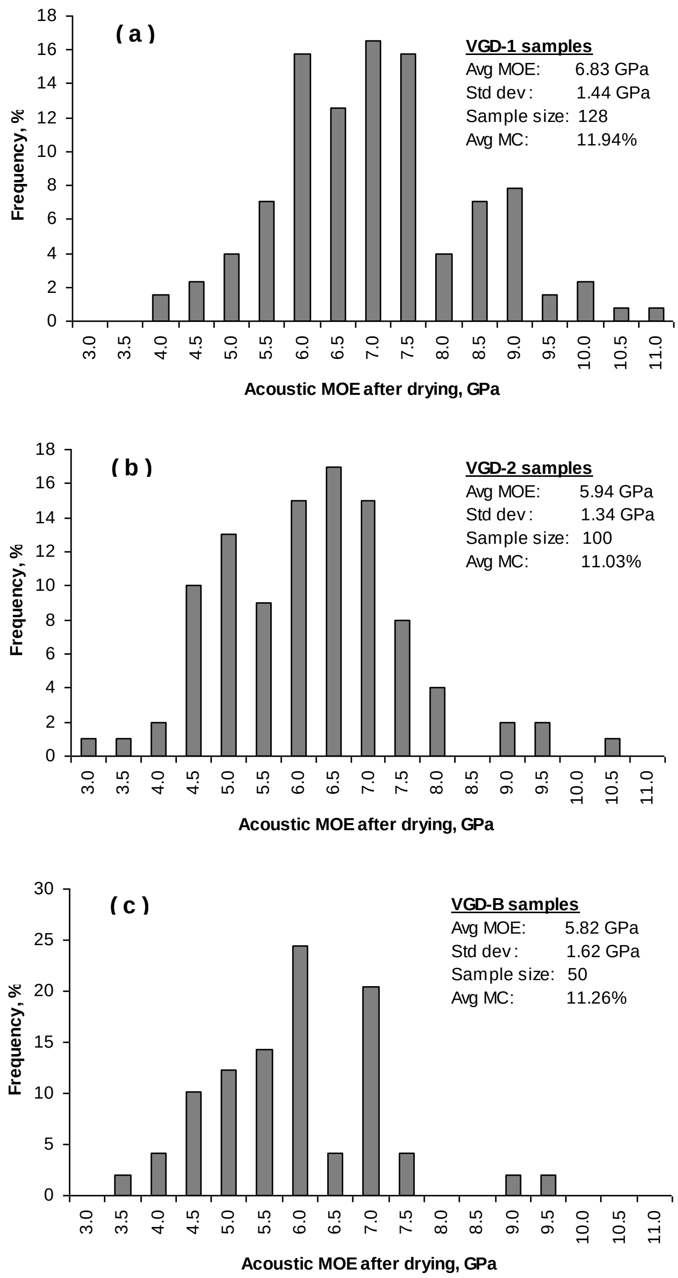


Figure 6-14: Distribution of acoustic MOE values based on timber visual grading results: (a) VGD-1, (b) VGD-2 and (c) VGD-B

6.3.3 Influence of corewood proportion on acoustic properties

Based on corewood proportion contained in cross-section of each board, all radiata pine timbers were segregated into 4 groups. The variation of acoustic properties of radiata pine as a function of corewood proportion is presented in Table 6-4.

Table 6-4: Variation of acoustic properties with corewood proportion

Corewood proportion	Acoustic velocity, km/s				Acoustic MOE, Gpa			
	Green		Dry		Green		Dry	
	Ave	Std	Ave	Std	Ave	Std	Ave	Std
CP90	2.78	0.27	3.52	0.41	4.92	1.07	5.42	1.17
CP70	2.91	0.28	3.75	0.34	5.57	1.07	6.11	1.10
CP30	2.81	0.26	3.83	0.35	6.04	1.39	6.50	1.31
CP10	2.83	0.27	3.90	0.42	6.20	1.48	6.86	1.45

It can be seen from Table 6-4 that the corewood proportion had significant influence on acoustic properties of radiata pine timber. This influence was more obvious for the dry board acoustic velocity, and acoustic MOE of both green and dry boards in which a significant increasing trend was found with decreasing of the corewood proportion. However, the relationship was not consistent with green acoustic velocity results, which could be affected by the uneven distribution of green MC along timber length.

6.3.4 Correlation between acoustic properties and timber distortion

In distortion measurement (see Figure 6-1), only 7.1% of radiata pine timber was graded as Grade A, which is also termed as Select Structural Grade, and more than 45% of the kiln-dried timber was rejected (Grade D). If there was a method to pre-sort those warp-prone radiata pine timbers before drying, the potentially rejected boards could be used for other purpose such as MDF (medium density fibreboard) or pulp and paper. In addition energy could be saved for timber drying.

Table 6-5: Variation of acoustic properties with distortion grade

Distortion Grade	Acoustic velocity (green), km/s				Acoustic MOE (dry), GPa			
	Ave	Stdev	Max	Min	Ave	Stdev	Max	Min
A	3.14	0.37	3.94	2.64	8.46	1.11	10.65	6.72
B	2.95	0.26	4.08	2.50	6.91	0.96	9.41	4.97
C	2.89	0.29	3.64	2.37	6.56	1.36	10.63	2.98
D	2.76	0.24	3.36	2.25	5.62	1.39	13.58	3.10

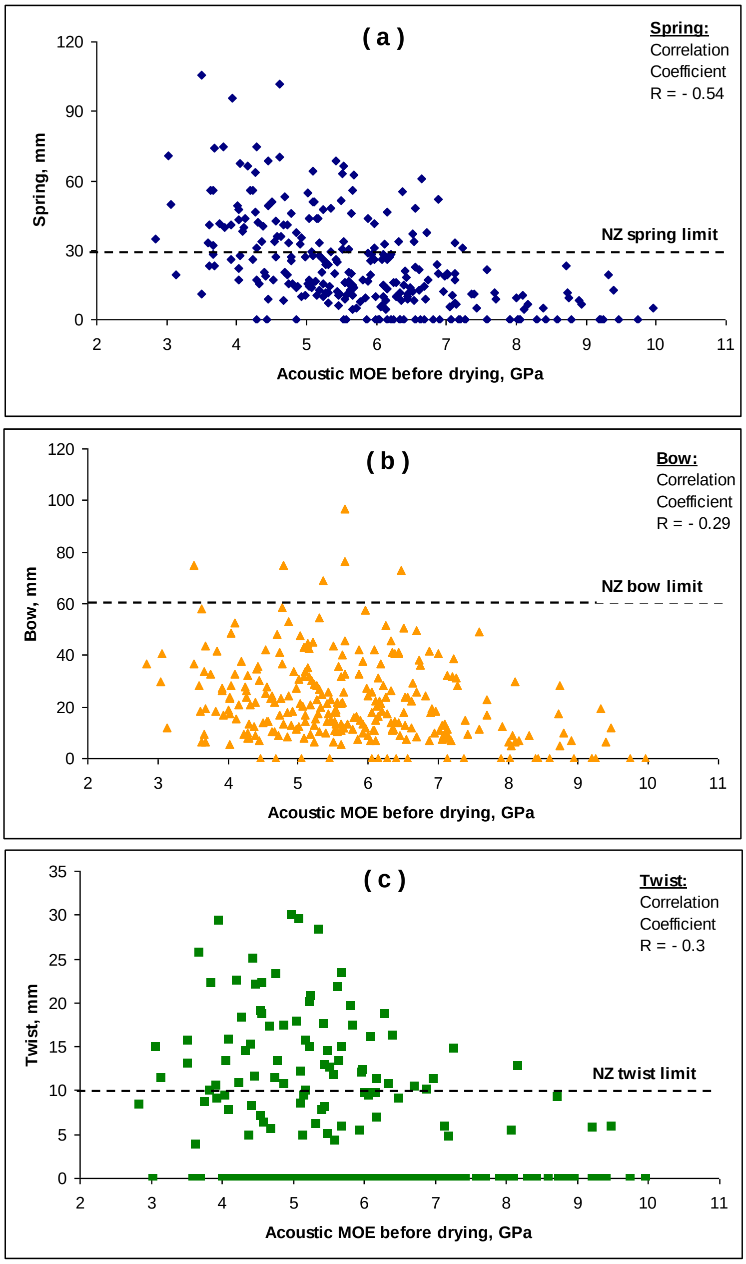


Figure 6-15: Correlation of acoustic MOE with timber distortion in forms of spring (a), bow (b) and twist (c).

Table 6-5 summarized the acoustic velocity and acoustic MOE data form the four distortion grade groups. It is shown that both acoustic velocity and acoustic MOE can be correlated to the timber grade positively. Grade A timber had the highest average acoustic velocity value in green condition, it also achieved the highest average acoustic MOE after drying. As the extent of timber distortion increased, both mean acoustic velocity and mean acoustic MOE decreased.

Figure 6-15 illustrates the relationship between acoustic MOE of green board and distortion result of radiata pine timber, in forms of spring, bow and twist. The dashed line in the diagram shows the New Zealand permissive distortion limit of structure timbers according to timber grading rules.

From the Figure 6-15, a significant negative correlation (R = - 0.54) was plotted between acoustic MOE of green radiata pine timber and spring. The relationship between acoustic MOE and bow (R = -0.29) and twist (R = -0.3) was also clearly observed although it was less significant than for spring. For radiata pine timbers, excessive distortion was most likely to be found in low acoustic MOE rang. The result proved that acoustic velocity could be used to pro-sort warp-prone radiata pine board before timber drying.

Chapter 7 Comparisons of Douglas-fir and Radiata Pine

In this chapter, stability properties of Douglas-fir and radiata pine were compared for the small clear samples results. Stability performance of their timber of 100mm × 50 mm × 4.8m was also compared under the commercial practice in sawing and drying.

7.1 Comparisons on the results of small clear wood sample study

In small clear wood samples study, average green moisture content and basic density of Douglas-fir and radiata pine samples were determined. As a result of high percentage of heartwood content, the averaged green MC of Douglas-fir in this study was 55.7% which was much lower than the averaged value of radiata pine (118.12%). In another words, it takes much less energy to dry Douglas-fir boards to a similar target MC than radiata pine boards. Wood density is less variable from pith to bark in Douglas-fir trees than radiata pine, and this reduces the undesirable corewood characteristics.

Wood shrinkage from green values with moisture content to the values at oven-dried condition was analysed and presented in this study. Variations of oven-dried shrinkage within tree are illustrated in Figure 7-1 for Douglas-fir and in Figure 7-2 for radiata pine. For two species, the longitudinal shrinkage decreased from pith to bark, while tangential and radial shrinkage increased from pith to bark. For both species, the longitudinal shrinkage of the bottom disc (termed as 0 m) was much larger than those of other stem heights although this difference for Douglas-fir was less than that for radiata pine. Variation of tangential and radial shrinkage along the stem height was not consistent.

Along the cross section radius from pith to bark, the longitudinal shrinkage and its gradient were the largest near the pith or corewood area, where spiral grain angle and microfibril angle are high as reported by Cown et al. (1991) and Donaldson (1992, 1993). However, the extent of the longitudinal shrinkage and variation for Douglas-fir was much less than those for radiata pine.

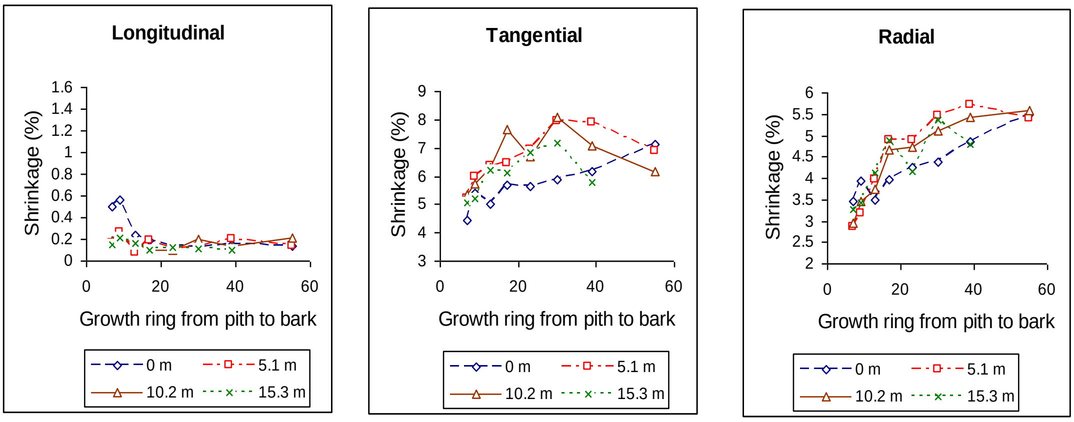


Figure 7-1: Variation of oven dry shrinkage for Douglas fir wood

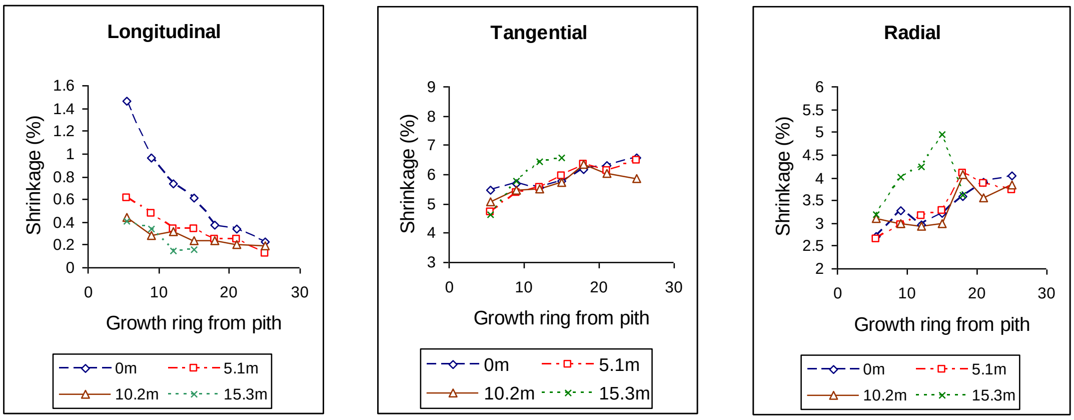


Figure 7-2: Variation of oven dry shrinkage for radiata pine wood

Two important points have been found from this study:

- Douglas fir has much lower longitudinal shrinkage than radiata pine. Except for the bottom disc, the average longitudinal shrinkage for Douglas fir is less than 0.3% from green to oven dry and 80% samples are between 0.1% and 0.2% whereas most of the radiata pine samples have the longitudinal shrinkage between 0.2% and 0.6%.
- The bottom disc has higher longitudinal shrinkage in the corewood and transition wood with values for Douglas fir from 0.1% to 0.6% and radiata pine from 0.8% to 1.6% at oven dry.

In the experiments, it was observed that the width of each growth ring of radiata pine was larger than that of Douglas-fir, thus the small clear samples of radiata pine contained less growth rings than those of Douglas-fir. In this way, the corewood samples of Douglas-fir may contain some transition wood thus the shrinkage variation is flattened to certain extent.

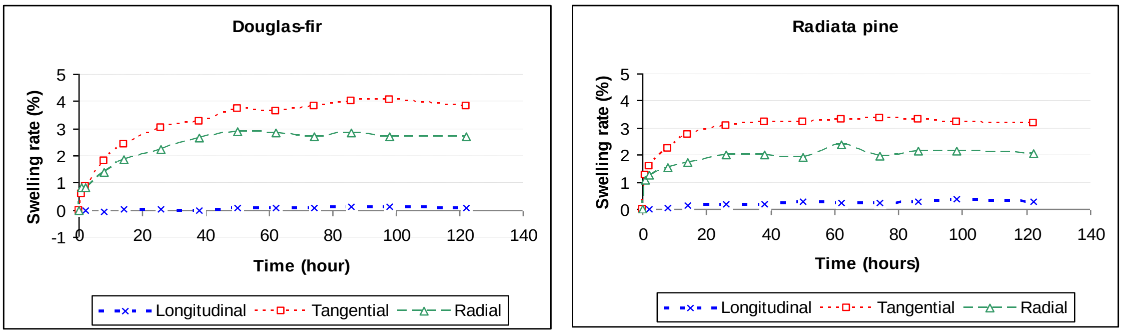


Figure 7-3: Swelling of Doulas-fir and radiata pine samples in water bath at 20°C

The swelling of Douglas-fir and radiata pine wood in water bath condition was obtained in this study. Water repellency property was tested in a temperature controlled water bath for both Douglas-fir and radiata pine. It can be seen in Figure 7-3 for the two species, the tangential and radial swelling increased rapidly in the first 2 hours, and then gradually reached their maximum swelling rates. The variation of longitudinal swelling for both species was not generally wide.

The demanding time for Douglas-fir samples to achieve maximum water swelling was over 48 hours, while it only took less than 24 hours for radiata pine samples to obtain the maximum value. This result was expected as Douglas-fir performed better water repellency property than radiata pine.

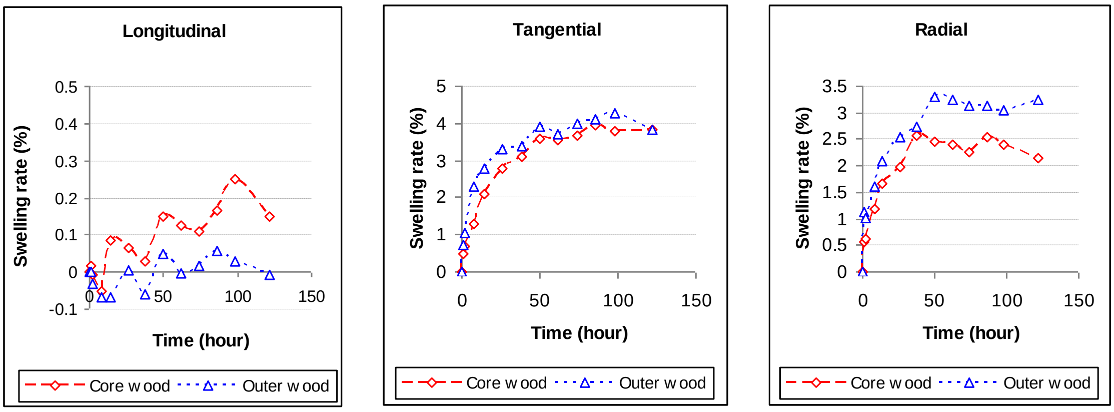


Figure 7-4: Water swelling of corewood and outerwood for Douglas-fir.

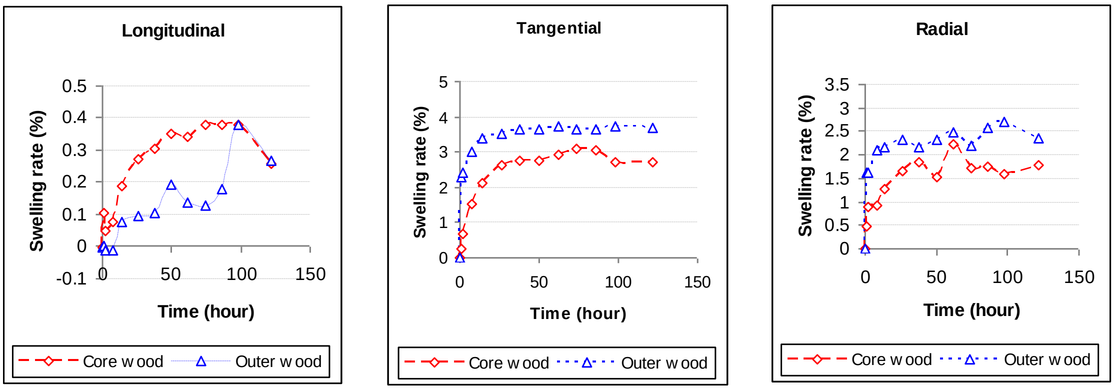


Figure 7-5: Water swelling of corewood and outerwood for radiata pine

The water swell behaviour of corewood and outerwood for the two species is examined and the results are shown in Figure 7-4 for Douglas-fir and in Figure 7-5 for radiata pine. From these figures, it is seen that the outerwood tended to swell more in tangential and radial directions, while it showed lower longitudinal swelling rate than the corewood. The reason for this would be higher spiral grain and microfibril angle in the corewood area. The maximum swelling values in tangential and radial directions for Douglas-fir were around 4% and 3 %, respectively. These values were slightly higher than those for radiata pine (3.2% and 2.1%). Longitudinal swelling data shows continuous increasing trend in about 100 hours, even when tangential and radial swelling had achieved maximum values.

Important points to be considered in this study:

- Douglas-fir absorbs less water than radiata pine in water immersion and the initial water absorption for Douglas-fir increases slower that radiata pine. However, the long term swelling of Douglas-Fir was higher than radiata pine in both radial and tangential directions.
- Corewood has higher longitudinal swelling and lower tangential/radial swelling than outerwood. This is truce for both species.
- Longitudinal swelling of both Douglas-fir and radiata pine tends to keep increasing with elapsed time.

7.2 Comparison on the results of full-sized timber study

After sawing, all the timber samples were visually graded into VGD-1, VGD-2 and VGD-B grade following AU/NZ visual grading standard. As shown in Figure 7-6, 86.6% of Douglas fir timbers were visually graded as high stiffness class timber, only about 2% were visually rejected from structural timber. However, more than 17% of radiata pine timbers were discarded in visual grading stage.

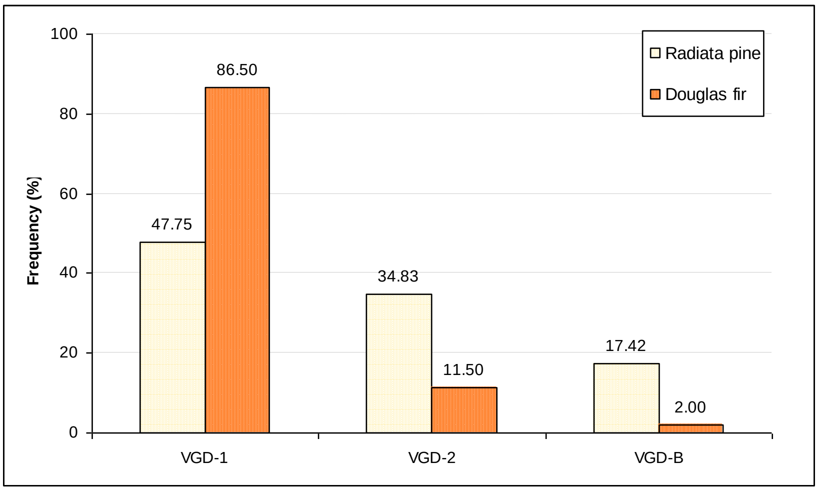


Figure 7-6: Comparison of Douglas fir and radiata pine on NZ visual grading results before timber drying

After timber drying, shrinkage values were determined from timber samples for both species. Table 7-1 illustrates the tangential and radial shrinkage obtained from full-sized Douglas-fir and radiata pine timbers. The flat-sawn and quarter-sawn timbers were identified based on the ring orientation of most growth rings over the end sections. With similar trend as for small clear sample studies, Douglas-fir and radiata pine timbers showed, in general, higher tangential shrinkage than radial shrinkage except for the boards of high corewood proportion. Corewood proportion has significant impact on shrinkage result for flat-sawn timbers of both species, but less for quarter-sawn timbers.

Table 7-1: Shrinkages of Douglas-fir and radiata pine full-sized timber

Species	Group	Flat-sawn timber			Quarter-sawn timber		
		MC (%)	TS (%)*	RS (%)**	MC (%)	TS (%)*	RS (%)**
Douglas-fir	C90	14.4(0.89)	1.58(0.59)	1.60(0.58)	16.0(1.21)	1.78(0.73)	1.80(1.09)
	C70	15.1(0.97)	1.85(0.35)	1.80(0.30)	15.1(1.35)	1.31(0.26)	1.10(0.20)
	C30	15.0(1.32)	1.82(0.35)	1.70(0.35)	16.1(0.36)	1.44(0.41)	1.21(0.26)
	C10	16.2(1.31)	1.95(0.24)	1.71(0.27)	15.6(0.07)	1.78(0.32)	1.51(0.35)
Radiata pine	C90	10.8(0.74)	1.89(0.54)	1.76(0.40)	11.3(0.31)	2.01(0.71)	1.88(0.23)
	C70	11.1(0.70)	2.23(0.39)	2.17(0.39)	11.4(0.66)	1.84(0.23)	1.73(0.25)
	C30	11.5(1.09)	2.40(0.48)	2.22(0.42)	12.0(0.09)	1.90(0.54)	1.78(0.56)
	C10	11.1(0.66)	2.82(0.53)	2.35(0.56)	11.2(0.12)	2.20(0.27)	1.70(0.20)

**TS: Tangential shrinkage* ***RS: Radial shrinkage*

Note: Numbers in brackets are standard deviation.

The tangential and radial shrinkage obtained from the flat-sawn timber both increased with decrease of the corewood proportion which can be traced to the local shrinkage variation in radius direction. However, no clear trend was found with the quarter-sawn timber, possibly due to the larger number of growth rings contained in the quarter sawn timber thus the variation in the radius direction was smoothed out. In addition, the difference between tangential shrinkage and radial shrinkage is much less in the full sized boards than in the small clear samples. This is again due to the growth ring orientation with many boards having growth rings orientated between ideal flat sawn and quarter sawn.

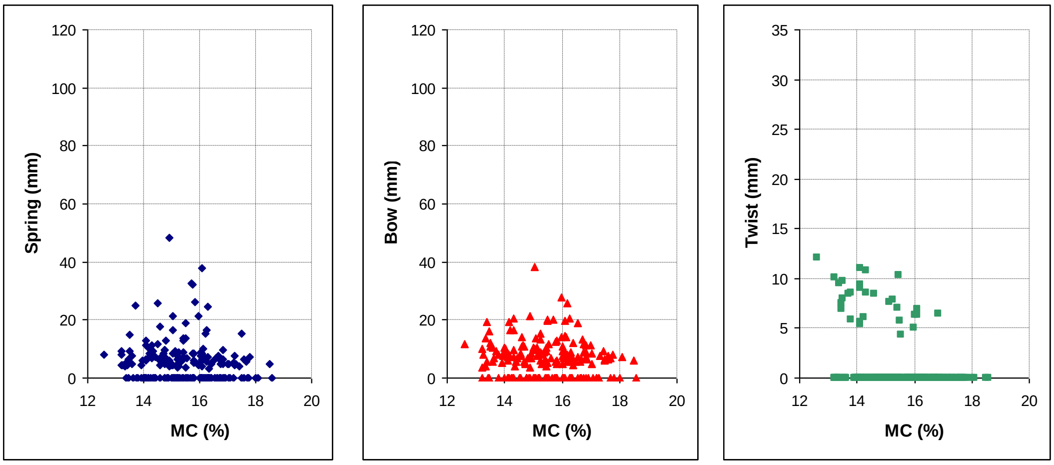


Figure 7-7: Spring, bow and twist of full-sized Douglas fir timber as a function of MC

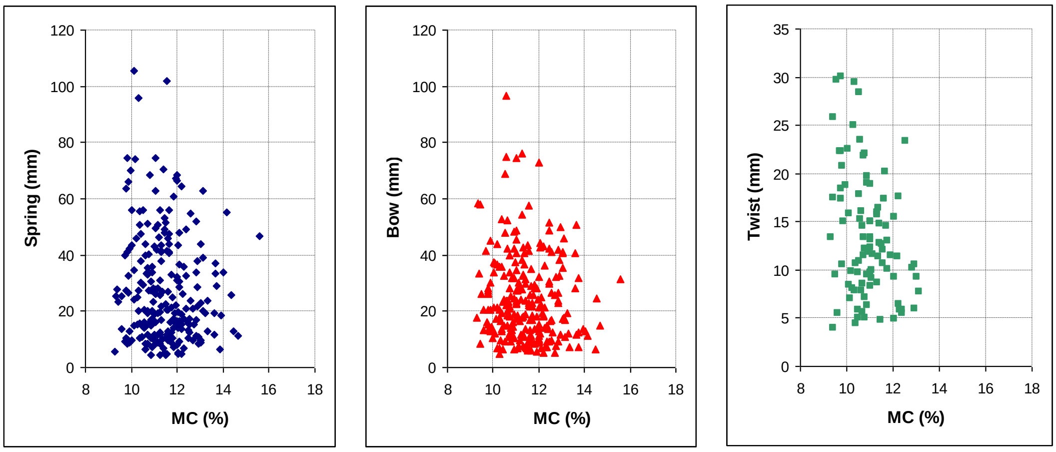


Figure 7-8: Spring, bow and twist of full-sized radiata pine timber as a function of MC

The distortion results of bow, spring and twists of all of the full sized boards are shown in Figure 7-7 for Douglas-fir and in Figure 7-8 for radiata pine. It is interesting to note from Figure 7-7 that the final MC for Douglas fir in the range of 13 – 18% did not have significant impact on the distortion although a negative trend was observed for radiata pine in Figure 7-8 where MC in the range of 9 – 15% shows distortion increasing with decrease in moisture content.

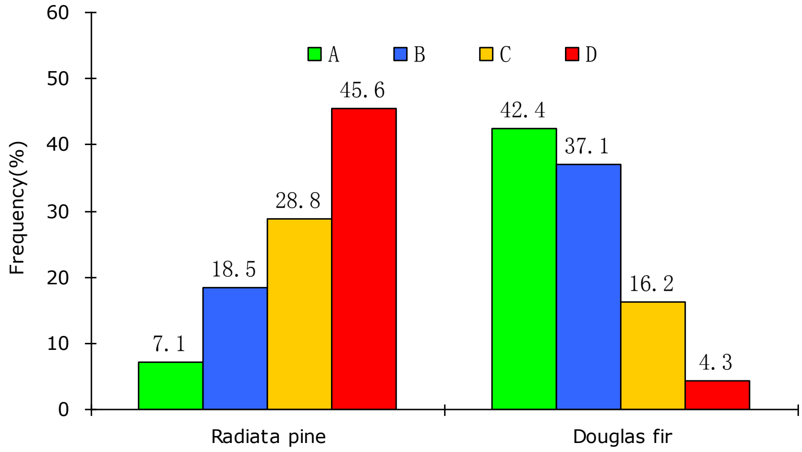


Figure 7-9: Grading of timber according to distortion tolerance

In Figure 7-9, the proportion of each distortion grade is illustrated both for Doulas-fir and for radiata pine. From these results, it is clearly shown that Douglas-fir timbers were straighter with lower levels of distortion than radiata pine timbers at similar final moisture content. The percentage of Grade D timbers (rejection rate) received in this study was 4.3% for Douglas-fir, while the corresponding value for radiata pine was 45.6%. This difference can be related to the difference in longitudinal shrinkage and shrinkage variations between these two species. As mentioned in previous section, the narrow growth ring in the Douglas-fir also contributed to the better stability performance. Although the diameter of logs were almost the same for two species, the age of Douglas-fir tree samples (60-year-old) in this study was much older than that of radiata samples (26-year-old), thus it was expected there were more mature wood in Douglas-fir than in radiata pine.

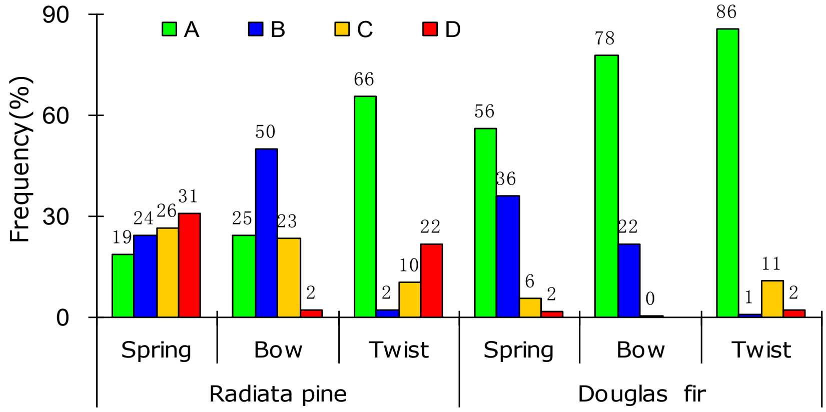


Figure 7-10: Distribution of distortion forms for radiata pine and Douglas-fir timber

Further analysis of the timber distortion by individual categories (bow, spring, twist) is shown in Figure 7-10. The analysis results show that spring and twist are the main reasons for the distortion rejection for both radiata pine and Douglas-fir boards. Bow is not considered to be an issue for both species. The distortion of bow and spring is closely related to the longitudinal shrinkage and its variability as shown in Figure 7-1 and Figure 7-2. Twist is more influenced by spiral grain angle which was not investigated in this study.

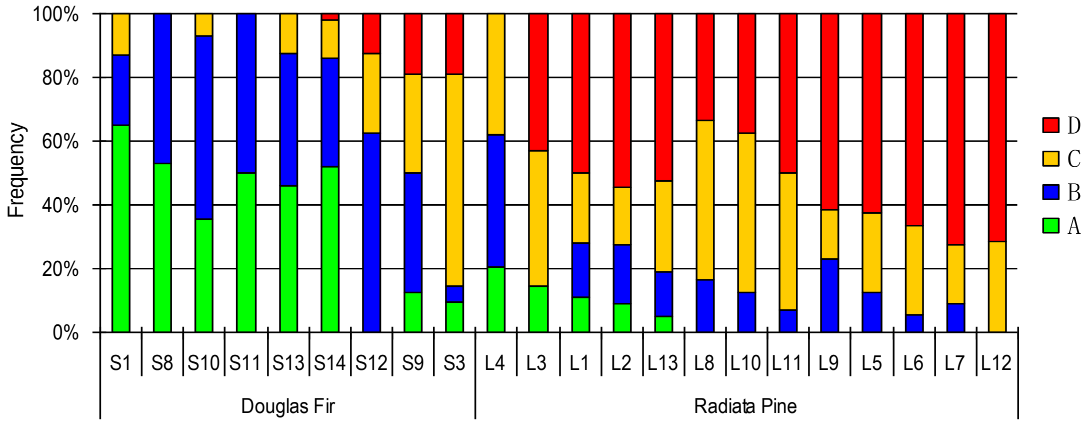


Figure 7-11: Distribution of distortion result within a tree and between trees

Results of shape stability performance from each sample tree of both species were shown in Figure 7-11. From the results, it is found that the distortion varied significantly between trees for both species. For Douglas-fir, timbers from trees S8 and S11 showed excellent shape stability with all of the timber falling into Grade A and Grade B while timbers from tree S3 had excessive distortion with more than 85% of the timbers falling to Grade C (67%) and Grade D (19%). For radiata pine, timbers from tree L4 showed the good stability performance with the 21% Grade A, 45% Grade B and 34% Grade C. It is most noticeable that for radiata pine, most of the trees did not produce Grade A timbers and small proportion of Grade B timbers, especially for tree L5, L6, L7, L9 and L12 with the worst rejection rate over 60%. The between-tree variation of timber distortion is related to the variations of shrinkage characteristics as well as other properties such as spiral grain angle. Cown (1992) reported that the spiral grain angle varied greatly between trees for radiata pine.

Figure 7-12 shows variation of timber distortion grade with stem height for both Douglas-fir and radiata pine trees. Since greater longitudinal shrinkage was found in butt disc samples as shown in Figure 7-1 and 7-2, it was expected that the timbers cut from butt log should have more distortion rejections. However, the result shows that this height effect is too isolated to strongly influence full-size timbers' distortion. For radiata pine, the timber rejection rate tended to increase with stem heights. The distortion results of Douglas-fir samples did not show a clear variation trend thus the influence of tree height influence may be ignored. This difference between two species may be caused by great variation between trees as described in previous section.

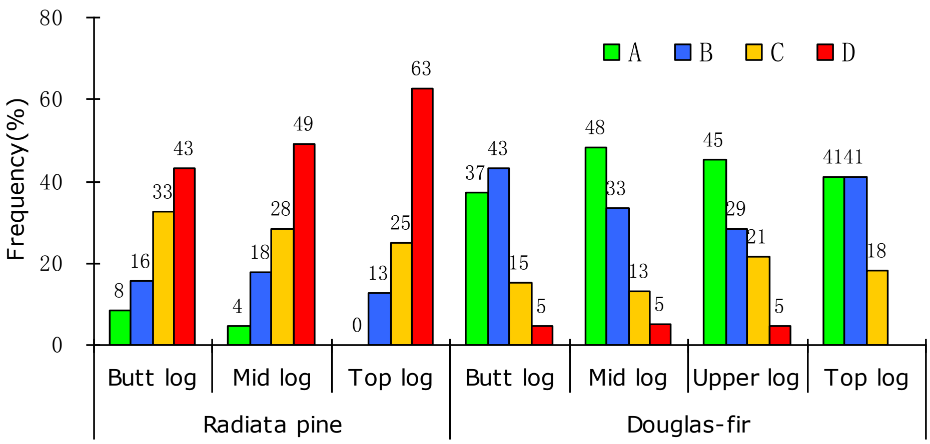


Figure 7-12: Effect of stem height on timber distortion

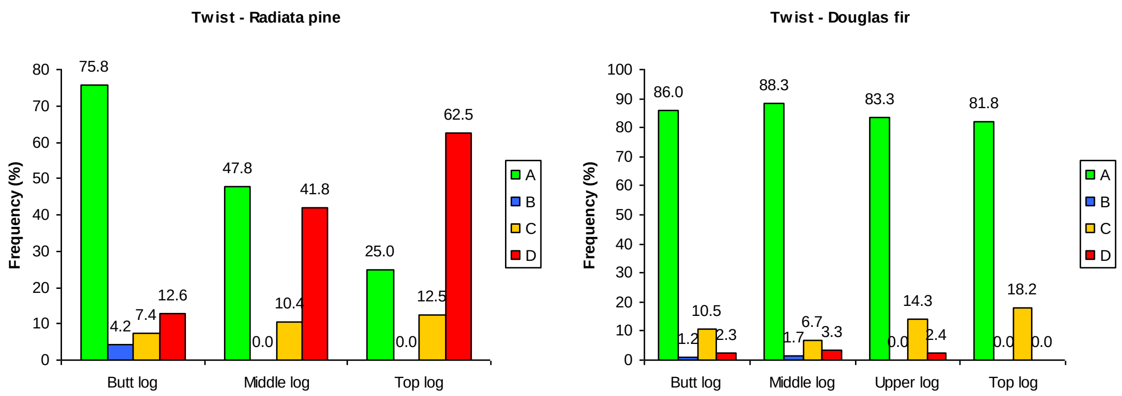


Figure 7-13: Variation of wood twist with stem heights

It was reported by Xu (2004) that tree heights showed clear influence on twist. Timbers from top log tended to produce higher twist, as spiral grain can be significant (> 6^{o}). The same result was found for radiata pine timbers in this study, but was not clearly observed from Douglas-fir timbers. As shown in Figure 7-13, radiata pine samples showed increasing trend of timber distortion in twist when log height was increased, while Douglas-fir samples presented a fairly steady twist result along longitudinal direction. Therefore, shrinkage alone is not sufficient to quantify the distortion trend. Shrinkage variation and spiral grain angle together can play an important role in the timber distortion. Based on the current study results, tree height is not recommended as a criterion for log sorting.

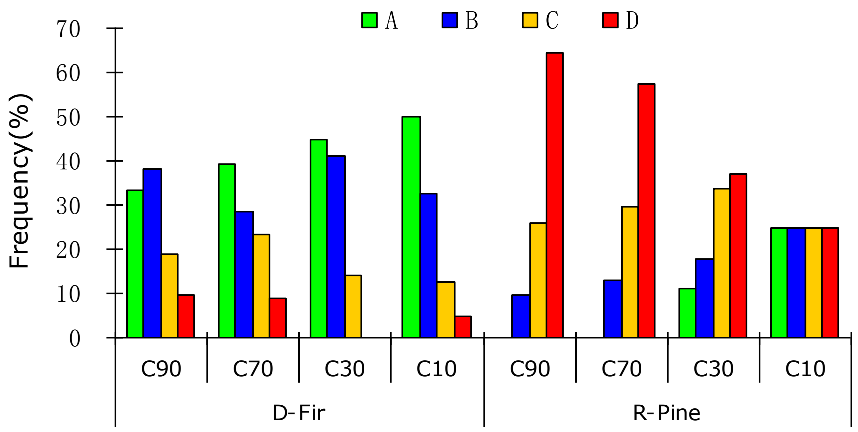


Figure 7-14: Effect of corewood proportion on timber distortion

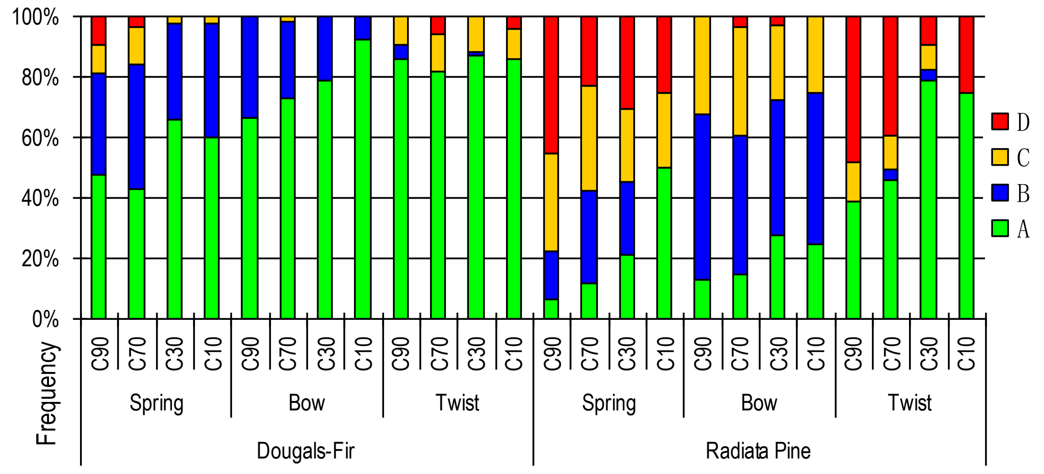


Figure 7-15: Comparison of effect of corewood proportion on spring/bow/twist

The distribution of timber distortion grades as a function of corewood proportion is shown in Figure 7-14 which confirmed a clear trend that corewood proportion has negative impact on the timber stability for both Douglas-fir and radiata pine. The timber quality degradation caused by the distortion worsened with the increase of the corewood proportion. This can be explained by combined effect of high longitudinal shrinkage, shrinkage variability and high spiral grain angle in the corewood. This result confirmed that the corewood proportion could be used as one of criterions for timber sorting before drying to reduce the degradation. Special drying technology should be adopted for the timber with high corewood proportion or the board with high corewood proportion should be used for wood composites or pulp and paper.

Figure 7-15 illustrates the effects of corewood proportion on different forms of distortion. For Douglas-fir, it seems that spring and bow were correlated to the corewood proportion with high level of significance while twist did not show such obvious correlation. For radiata pine samples, spring, bow and twist all showed a certain extent correlation to the corewood proportion.

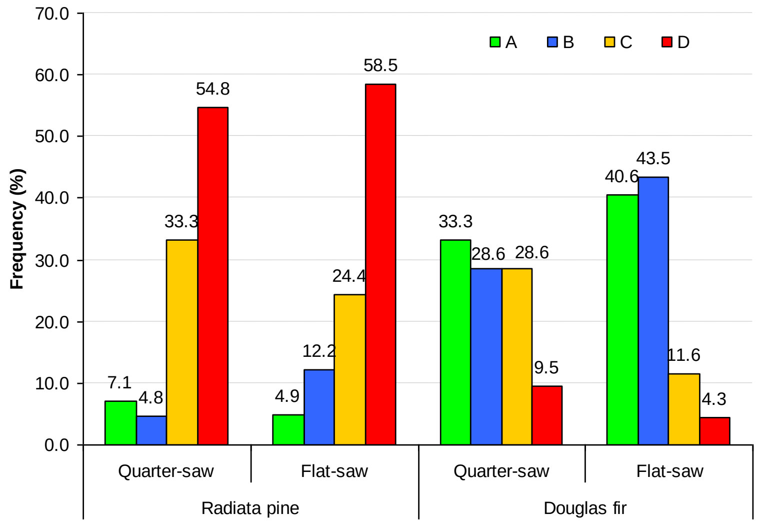


Figure 7-16: Effect of sawing pattern on the wood distortion

Figure 7-6 shows the distortion result from different sawing patterns for radiata pine and Douglas-fir. The results show that drying distortion for both species was strongly influenced by the sawing pattern. Timbers with quarter-saw pattern tended to generate more distortion boards than those with flat-saw pattern. This influence was more obvious for Douglas-fir samples. The total proportion of Grade C and Grade D timbers received from quarter-saw pattern for Douglas-fir was 38.1%, while this value from flat-saw pattern was only 15.9%.

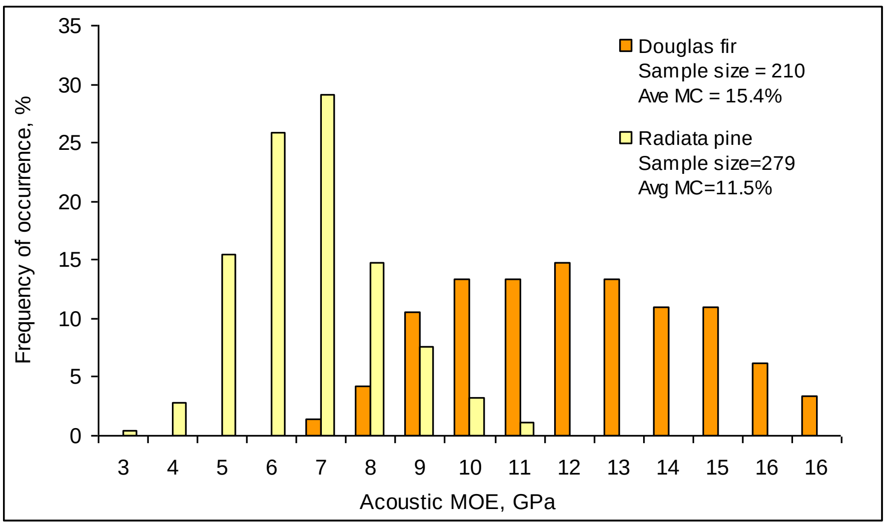


Figure 7-17: Distribution of acoustic MOE of dry timber

The distribution of acoustic MOE (GPa) results received from full-timber study is shown in Figure 7-17. Acoustic MOE of a board was calculated from the acoustic velocity (V) and wood density (ρ) by:

$MOE = \rho \times V^2$.

Douglas fir timbers show much higher average acoustic MOE value (11.47GPa) than radiata pine timbers (6.33GPa) at similar MC. Acoustic MOE results of radiata pine timbers ranged from 3GPa to 11GPa with almost 85% of the samples having acoustic MOE between 5GPa and 8GPa. In contrast, the acoustic MOE for Douglas-fir was distributed relatively evenly in the rang of 7GPa to 16GPa.

Chapter 8 . Conclusions and Recommendations

Stability related properties and performance of dry timber of Douglas-fir and radiata pine were experimentally investigated, and the results were compared in this study. From lab experiments, basic wood properties of basic density, green moisture content, shrinkage, equilibrium moisture content (EMC) and fibre saturation point (FSP) were studied for both species. In sawmill studies, timber shape stability (drying distortion in forms of spring, bow and twist) and acoustic properties were measured. The influence of corewood proportion, log heights, final MC and sawn patterns on timber distortion was also examined. The information observed from the lab studies was used to explain the timber stability performance in the sawmill study.

8.1 Database of stability related properties of Douglas-fir

This study has obtained property data of Douglas-fir that are believed to have influence on timber stability performance.

From this project, the heartwood/sapwood boundary was found to be at 25th to 30th growth rings. The average heartwood green moisture content of Douglas-fir was 44.8% and the average value of sapwood was 80.7%. The mean basic density of Douglas-fir was 446.06 kg m^{-3}. It varied significantly within a tree and between trees. In the disc radial direction, the average basic density was low near the pith and its lowest value was found around the 8th growth ring from which the density increased towards the bark. In the tree height direction, the overall average basic density tended to be the highest within the butt discs, and decreased along the stem height. However, the variation above 5.1 m high was not significant.

From this study, it was found that the mean shrinkage of Douglas-fir in longitudinal, tangential and radial directions from green to oven-dried were 0.2%, 6.05% and 4.15%, respectively. The corresponding shrinkage values from green to 12% MC were 0.12%, 2.97% and 1.78%. The bottom disc was found to have the highest longitudinal shrinkage, but the tangential and radial shrinkage values were lower than those at higher stem positions. In all stem heights, the highest longitudinal shrinkage value was found near pith and from 15th growth ring outwards, the longitudinal shrinkage value tended to be relatively constant at about 0.2%. The overall value of the tangential and the radial shrinkage shows a trend of increase from pith to bark. The influence of tree height on the shrinkage value was not clearly observed for Douglas-fir samples in this study.

The EMC values of Douglas-fir samples during desorption at a constant temperature of 30^{o}C and RH of 40%, 50%, 65% and 85% were 8.1%, 9.2%, 11.9% and 17.1%, respectively. The corresponding values during absorption were 5.6%, 6.6%, 8.2% and 12%. The samples from bottom discs showed much lower EMC value than those from other stem heights. Sapwood (from 30th growth ring and outwards) tended to have higher EMC values than the heartwood at a given RH.

The average FSP of 24.47% MC for Douglas-fir at 30^{o}C was determined from the correlation plot of the tangential shrinkage against the moisture content. The FSP value varies within a tree and between trees. The highest FSP was found in butt disc, the value tended to decrease with the stem height.

8.2 Comparison of stability related properties of Douglas-fir with radiata pine

The results from small sample study confirmed that Douglas-fir is much stronger, has lower longitudinal shrinkage in corewood and better dimensional stability than radiate pine although there is significant variability in the shrinkage for both Douglas-fir and radiate pine. In water immersion tests, Douglas-fir has performed better water repellency property than radiata pine.

Under the same commercial practice in sawing and kiln drying, it is clearly shown that Douglas-fir timbers were straighter with lower levels of distortion than radiata pine at similar final moisture content. It is also interesting to note that the final moisture content in a range of 13-18% for Douglas-fir did not have significant impact on timber distortion but a negative trend was observed for radiata pine with MC in a range of 9 -14%. Tree heights showed clear influence on twist for radiata pine timbers, but it was not clearly observed from Douglas-fir timbers. Corewood proportion is found to have negative impact on the timber distortion for both Douglas-fir and radiata pine. Douglas-fir timbers showed much higher average acoustic MOE value than radiata pine timbers at similar final moisture content.

The outcome from this project includes better understanding of Douglas-fir for structural applications. The conclusion can be drawn that Douglas-fir has superior quality for its strength, durability and moisture resistance. Douglas-fir is also claimed to have uniform properties and thus to be more stable compared to radiata pine.

8.3 Recommendations on pre-sorting of log and timbers

Because of the various proportion of corewood, the shrinkage varied greatly in longitudinal and radial directions for the two species. This variation caused the difference of distortion between corewood, outerwood and transition wood, but the difference between butt log, middle log and top log is inconsistent. Therefore, it is recommended that the corewood proportion to be a criterion for the timber pre-sorting.

Variation of stability performance between trees was also found to be significant for the two species, and methods need to be developed for log sorting as well to reduce the timber distortion degradation. Non-destructive testing method such as acoustic tool may be offered as a new approach for sorting logs to manufacture and customer demands, but it is also necessary to be aware of the significant difference between species.

New Zealand’s forestry is almost total reliance on radiata pine, which makes up nearly 90% of its commercial forests. Douglas-fir can be regarded as the first place alternative wood specie in this country for its superior stability properties and performance, and further studies should be undertaken at larger scales to verify the performance in a building structure.

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